THE GEOLOGY OF NEW HAMPSHIRE

PART II - BEDROCK GEOLOGY

By

Marland P. Billings

Published by THE NEW HAMPSHIRE STATE PLANNING AND DEVELOPMENT COMMISSION

Frontispiece—Aerial photograph looking south over Profile (Cannon) Mountain; Franconia Notch to the left. Relief is 2,000 feet. Great swaths through the forests are ski trails.

THE GEOLOGY
OF
NEW HAMPSHIRE

by

Marland P. Billings

Originally published by the

State Planning and Development Commission

1956

Reprinted 1962

Reprinted 1968

Reprinted by

Division of Forests and Lands

Department of Resources and Economic Development

Concord, New Hampshire

1980

NEW HAMPSHIRE DEPARTMENT OF RESOURCES and ECONOMIC DEVELOPMENT

George Gilman
Commissioner

Theodore Natti, *Director*
Division of Forests and Lands

Robert I. Davis
State Geologist

Concord, New Hampshire
1980

PREFACE

This publication is intended to explain more fully the accompanying geological map of New Hampshire. Although a geological map contains a large amount of information, it is apparent that its scope is necessarily limited.

This map of the bedrock geology of New Hampshire, the first to be published since 1877, has been made possible by the interest and zeal of many people. Among these are those geologists, gradute students and faculty from various colleges and universities, who spent two or more years investigating specific areas. They are too numerous to list here, but their names are given beneath the index map on the right-hand side of the sheet containing the geological map. Many others have given help and encouragement in various ways. Among these are the late Professor James W. Goldthwait of Dartmouth College, Dr. Harold M. Bannerman of the U. S. Geological Survey, and Professor T. R. Meyers of the University of New Hampshire. The former State Highway Commissioner of New Hampshire, Frederic E. Everett, as well as the former and present officials of the New Hampshire State Planning and Development Commission, likewise encouraged the program. Finally, the Geological Society of America, especially the secretary, Dr. Henry Aldrich, and the editor, Miss Agnes Creagh, have been most helpful in supporting the publication of the results of the many detailed investigations. Thanks are also due to Professor M. T. Heald of the University of West Virginia who cooperated with the writer in a reconnaissance study of the geology of parts of New Hampshire in 1951. Professor John B. Lyons of Dartmouth College, Dr. Harold M. Bannerman, and Professor T. R. Meyers kindly read the first draft of this publication and made numerous valuable suggestions for its improvement.

A brief word is desirable to explain the purpose of the accompanying geological map. In a sense, the present map is a by-product of efforts to understand the geological history of New Hampshire, that is, to learn the sequence in which the rock formations developed and the physical conditions under which they formed. It is increasingly apparent that such studies and the map accompanying this report are indispensable in planning the search for new mineral deposits. On the other hand, the reader should realize that detailed information concerning mineral deposits cannot be shown on the scale of this map. Such details will be found in Part III of the present series.

The finality of the accompanying geological map also needs discussion. It is always possible to improve a geological map. There are many reasons why modification is possible. Ideally, the geologist mapping an area should see every outcrop, but in a quarter-minute quadrangle (about 200 square miles) it would take a three-man field party ten years to find and map every outcrop. In many regions only 1% or 2% of the area displays outcrops of the bedrock; elsewhere the bedrock is buried by glacial deposits or river deposits from one to hundreds of feet thick. Who would undertake to prepare a street map of Boston if given spot information on only a few percent of the city? But the problem of correlation is most important; that is, is the slate in outcrop B the same as the slate in outcrop A; if not, is it lower or higher in the stratigraphy? The successful interpretation of the relationship between thousands of outcrops taxes the intelligence of any geologist investigating the geology of an area. Alternative interpretations are often possible.

With the gradual accumulation of new data in specific areas as the years go by, it is obvious that geological maps must be modified. Moreover, with the continuous forward march of science, it is necessary to reinterpret the old data and integrate it with new information. New ideas may greatly modify the interpretation of geological data. Finally, the ever changing and more exacting requirement of a growing economy demand reappraisal of our natural resources.

The manuscript copy of the map was submitted to the U. S. Geological Survey in January, 1953; hence, it represents facts known at that time. Since then the geologic mapping of the Manchester, Dover, and Exeter quadrangles has been completed. Field work has been initiated in the Dixville and Errol quadrangles. Much work remains to be done in mapping other parts of New Hampshire that have been covered only by reconnaissance methods (see index map accompanying the geological map). Moreover, with the progress of knowledge, it is apparent that revision of parts of some of the other quadrangles is highly desirable.

Cambridge, Massachusetts.

October 10, 1955

TABLE OF CONTENTS

ILLUSTRATIONS

TABLES

THE BEDROCK GEOLOGY OF NEW HAMPSHIRE

By MARLAND P. BILLINGS

INTRODUCTION

Location. New Hampshire lies entirely within the Appalachian Highlands, which extend northeasterly from Alabama on the southwest to Newfoundland on the northeast. Geologically, as shown in Figure 1, New Hampshire is in the midst of the Appalachian Province, halfway between the pre-Cambrian metamorphic and igneous rocks of the foreland, exposed in the Adirondack Mountains of New York and the Canadian Shield, and the Cretaceous and Cenozoic sediments of the Coastal Plain. Cutting diagonally across the trend of the Appalachians, New Hampshire offers an opportunity to study the deeply eroded core of a mountain system that first formed hundreds of millions of years ago. Here we find folded and faulted Paleozoic sedimentary and volcanic rocks that have been thoroughly metamorphosed and penetrated by large and small bodies of plutonic rocks. It is in regions such as this that geologists may hope to find some of the more significant clues to the causes of mountain building.

Physical Features. Although the details of the topography of New Hampshire are shown by 200 foot contour lines on the geological map accompanying this report, the general topographic features may be more readily grasped by referring to Figure 2. On the southeast is the Seaboard Lowland, 30 miles wide and less than 500 feet above sea level. The southern half of the rest of the state, although commonly assigned to the New England Upland (Fenneman, 1931, plate in pocket; 1938, Plate 1), can be readily divided into three topographic units. An eastern belt, from 5 to 35 miles wide, lies between 500 and 1,000 feet above sea level, although isolated mountains rise to nearly 3,000 feet. An intermediate belt, averaging 20 miles in width, lies mostly between 1,000 and 2,000 feet above sea level, with isolated peaks rising to more than 3,000 feet. Along the western border of the state the Connecticut Valley, less than 2,000 feet above sea level, is only a few miles wide.

Most of the northern half of the state is at least 1,000 feet

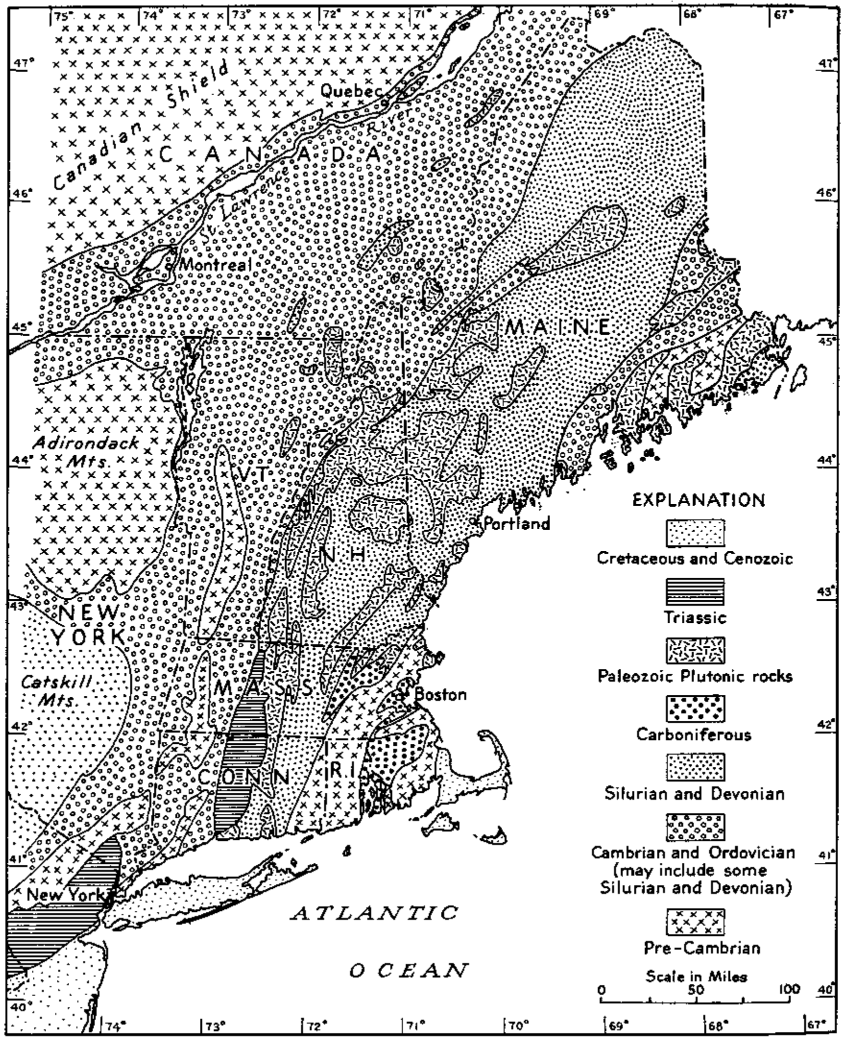

Figure 1. Geological sketch map of New England and adjacent areas. Shows position of New Hampshire in the Appalachian Province. The Cretaceous and Cenozoic rocks belong to the Coastal Plain. The pre-Cambrian rocks of the Adirondack Mountains are part of the Canadian Shield. All other rocks are part of the Appalachian Province. This is a very generalized map and is not intended to be detailed.

above sea level and much of it is more than 2,000 feet. The White Mountains, as commonly defined, occupy the north-central part of the state, attaining a maximum altitude of 6,288 feet on Mt. Washington. The mountains in the northernmost 50 miles of the

state, although assigned to the White Mountain section by Fenneman, are generally treated separately. No general name has been applied to them, although sometimes they are assigned to the Boundary Mountains, which extend into northwestern Maine and northeastern Vermont.

Most of New Hampshire, except for villages, cities, and farmlands, is heavily wooded. In general, only those summits in the White Mountains that reach altitudes greater than 4,800 feet are above timberline. But many lower peaks are barren rock, either because of forest fires or because the cutting of timber for pastures permitted erosion of the soil.

Although the rivers are not named on Figure 2, they can be readily identified. New Hampshire is bordered on the west by the west bank of the Connecticut River. The center of the southern half of the state is drained by the southerly flowing Merrimack River and its tributaries. The southeastern part of the state is drained by the Piscataqua River and its tributaries. Much of the eastern margin of the northern part of the state lies within the drainage basin of the Androscoggin River, which enters New Hampshire 30 miles south of the northeast tip of the state and leaves again 30 miles further south. The only other important river is the Saco, which drains the east-central part of the state. Of the total area of the state, 9,282 square miles, 41% is in the Merrimack drainage, 33% is in the Connecticut drainage, 9% is in the Saco drainage, 9% is in the Androscoggin drainage, and 8% is in the Piscataqua drainage.

The later stages in the evolution of New Hampshire, especially the carving of the existing landforms by streams and their modification by glaciers, are described in Part I of this report (J. W. Goldthwait et al., 1951).* Although in many places the glaciers have left deposits of drift (till, sand, gravel, and clay) that are troublesome to those geologists who are primarily concerned with the bedrock geology, the exposed rocks are very fresh, in contrast to the deeply weathered rocks that plague investigators of the geology of the Piedmont Province south of New York City.

* All references are given in alphabetical order on pages 156-166.

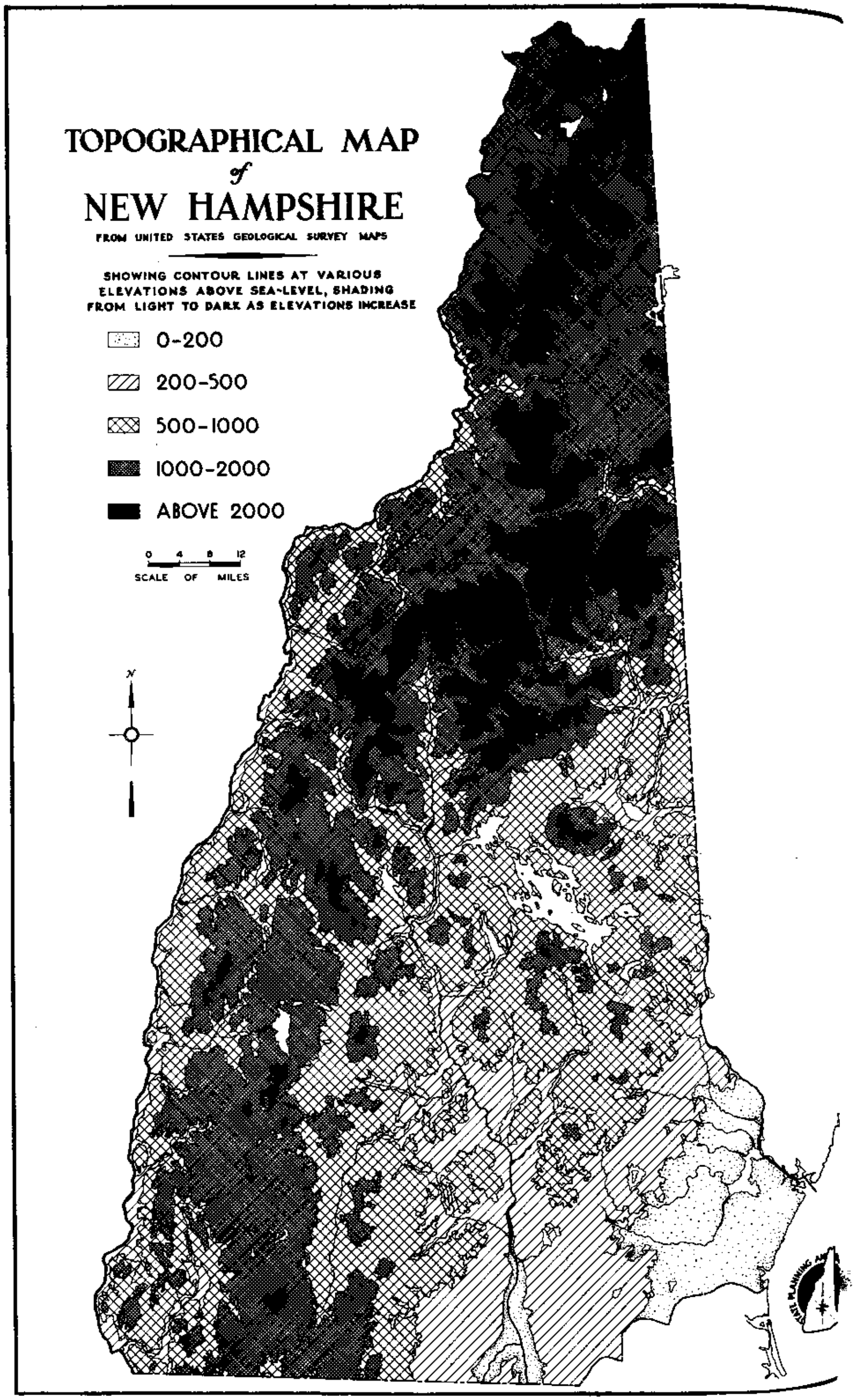

Figure 2. Physical features of New Hampshire. From "State Planning

STRATIGRAPHY

General Statement

The sedimentary and volcanic rocks that constitute the framework into which the plutonic rocks have been emplaced range in age from Ordovician (?) to Mississippian (?). Generalized columnar sections are given in Fig. 3 and 4. The Silurian and Devonian rocks are dated by fossils in New Hampshire. The Ordovician (?) rocks are dated by their relationship to fossiliferous rocks in Vermont and Quebec. The Ordovician (?) and Silurian (?) rocks in southeastern New Hampshire are dated in part by their relationship to the fossiliferous rocks in central Maine, and in part by their relationship to the fossiliferous rocks in western New Hampshire. The Mississippian (?) volcanics are dated by their relationship to Devonian rocks in New Hampshire and Pennsylvanian rocks in Massachusetts.

The Devonian and older sedimentary and volcanic rocks have been regionally metamorphosed. The grade of metamorphism differs considerably, from the chlorite zone at one extreme to the sillimanite zone at the other. For descriptive purposes the rocks have been assigned to five zones: the chlorite, biotite, garnet, staurolite, and sillimanite zones. These are, respectively, more or less the equivalents of the following subfacies in the facies classification: chlorite-muscovite, chlorite-biotite, chloritoid-almandite, staurolite-kyanite, and sillimanite-almandite subfacies (Turner and Verhoogen, 1951). The regional metamorphism thus greatly complicates the description of the rocks. Conceivably, each formation might appear in all five of the metamorphic zones. For structural reasons this happens in only a few instances, and most formations appear in only a few of the zones.

The Mississippian (?) volcanic rocks are younger than the regional metamorphism. They have probably been involved in some contact metamorphism, but apparently they have not undergone much change in mineralogy.

Vast quantities of plutonic rocks have been emplaced in the sedimentary and volcanic rocks. These plutonic rocks, although assigned to a large number of separate map-units, belong to seven major groups. The ages of some of these plutonic rocks, originally based on stratigraphic relations, have recently been confirmed by radioactive age determinations. The Newburyport quartz diorite is probably pre-Cambrian; the serpentine is possibly late Ordovician; the Highlandcroft plutonic series is late Ordovician; the Oliverian and New Hampshire plutonic series, as well as the plutonic rocks of southeastern New Hampshire, are Middle or Upper Devonian; and the White Mountain plutonic-volcanic series is Mississippian.

In the ensuing pages each sedimentary and volcanic formation is described under the following subheadings: name, distribution, lithology, thickness, and correlation. By correlation is meant the internal correlation within New Hampshire and adjacent parts of New England. In other words, these sections on correlation are concerned with the proof that the formation has been properly correlated within the limits of the map. It does not refer to the correlation with fossiliferous formations elsewhere.

Although the age of the various formations will be mentioned briefly under the subject of correlation, the main discussion of the age of the rocks is reserved for a separate section. Fossil localities are so few that the age of a formation is, in many cases, determined by its relation to fossiliferous rocks either within New Hampshire or, in some instances, in adjacent states and provinces. Hence, since the age of a formation is determined in many cases by regional relations, it seems best to discuss the entire subject in one place.

Western, Central and Northern New Hampshire

Ordovician (?)

General Statement

The formations that have been assigned to the Ordovician (?) on the geological map are the following: Waits River formation, Standing Pond volcanics, Gile Mountain formation, Meetinghouse slate, Orfordville formation, Albee formation, Ammonoosuc volcanics, and Partridge formation (Fig. 3).

Waits River Formation

Name. A formation that is very extensive in eastern Vermont was called the calciferous mica schist by Hitchcock et al (1861). Many decades later Richardson (1906) proposed the name Waits River limestone for a group of rocks exposed along the Waits River, in Vermont, which joins the Connecticut River 2 miles northwest of Piermont, New Hampshire. Because much of the rock in this formation is phyllite and sandy phyllite, whereas

SYSTEM	SERIES	FORMATION	COLUMNAR SECTION	LITHOLOGY WHERE LEAST METAMORPHOSED	THICKNESS IN FEET
MISSISSIPPIAN ?		Moat volcanics		Flows, tuffs, and breccias composed chiefly of light-gray, bluish-gray, and red rhyolite, black basalt, and dark-gray andesite, but including some red trachyte.	10,000+
		Unconformity			
DEVONIAN	Lower	Littleton formation	Dlv	Dark-gray slate and dark-gray sandstone. Dlv = volcanic rocks, including buff to white soda-rhyolite, soda rhyolite volcanic conglomerate, dark-green chlorite schist and lighter green chlorite-actinolite schist.	15,000±
SILURIAN	Middle	Fitch formation		Blue-gray limestone, white marble, buff slaty dolomite, gray calcareous slate, gray arenaceous limestone, white calcareous sandstone, gray slate, white arkose, and light-gray quartz conglomerate.	0-769
SILURIAN	Lower or Middle	Clough quartzite		Gray to white quartzite and quartz conglomerate.	0-1200
		Unconformity			
PRE-SILURIAN Probably Ordovician	Upper Ordovician?	Partridge formation		Chiefly dark-gray slate.	0-2000
PRE-SILURIAN Probably Ordovician	Upper Ordovician?	Ammonoosuc volcanics		Buff to white schistose soda-rhyolite tuff, breccia, and volcanic conglomerate; dark-green chlorite schist; dark-green chlorite-epidote schist; gray slate; gray impure quartzite.	2000-5000
PRE-SILURIAN Probably Ordovician	Upper Ordovician?	Albee formation		Light-green slate and phyllite, light-green quartzose phyllite, and light-green to white quartzite.	5000
PRE-SILURIAN Probably Ordovician	Middle Ordovician?	Orfordville formation	Oos, Oop, Ooh	Dark-gray slate and grey arenaceous slate. Oos = Sunday Mountain volcanic member, chiefly slaty soda-rhyolite tuff. Oop = Post Pond volcanic member, chiefly chlorite schist. Ooh = Hardy Hill quartzite, gray to white quartzite and quartz conglomerate.	3500-4000
		Fault ?			
PROBABLY MIDDLE ORDOVICIAN, POSSIBLY SILURIAN AND/OR DEVONIAN		Meetinghouse slate		Dark-gray slate with some thin beds of gray quartzite.	1100-2500
PROBABLY MIDDLE ORDOVICIAN, POSSIBLY SILURIAN AND/OR DEVONIAN		Gile Mountain formation		Dark-gray slate, dark-gray phyllite, gray arenaceous phyllite, and quartz-sericite schist.	6500
PROBABLY MIDDLE ORDOVICIAN, POSSIBLY SILURIAN AND/OR DEVONIAN		Standing Pond volcanics		Chiefly green chlorite schist, but including some buff to white soda-rhyolite tuff.	125-650
PROBABLY MIDDLE ORDOVICIAN, POSSIBLY SILURIAN AND/OR DEVONIAN		Waits River formation		Dark-gray phyllite, gray calcareous phyllite, and dark-brown arenaceous limestone.	4000+

Figure 3. Stratigraphic sequence in western, central, and northern New Hampshire.

pure limestones are relatively rare, Currier and Jahns (1941, p. 1491) proposed that this unit be called the Waits River formation.

Distribution. In New Hampshire the Waits River formation is confined to an area 16 miles long and 4 miles wide in Coös County between Pittsburg and Simms Stream.

Lithology. In this area the Waits River formation consists primarily of dark-gray phyllite, gray calcareous phyllite, and dark-brown arenaceous limestone. These three rocks are interbedded in layers that are a few inches to many feet thick. South of the biotite isograd the rocks contain small porphyroblasts of biotite.

Thickness. Sufficient work has not been done in northern New Hampshire to determine the thickness of this formation. In southeastern Vermont the thickness is given as 5,000 (?) feet (Billings, Rodgers and Thompson, 1952, p. 40); west of Hanover, the thickness is 4,000+ feet (Lyons, 1955, p. 108).

Correlation. These calcareous rocks in Coös County are isolated from the main belt of the Waits River formation in eastern Vermont (Fig. 6). But the rocks of the Waits River formation are very distinctive and unlike any other formation in central New England. These calcareous rocks in northern New Hampshire are consequently assigned to the Waits River formation because of lithologic similarity.

On the geologic map the Waits River formation is shown as Middle Ordovician (?). There is some possibility that the formation is Silurian and/or Lower Devonian.

Standing Pond Volcanics

Name. Doll (1944, p. 17) proposed that a band of metamorphosed mafic volcanics in the Strafford quadrangle in eastern Vermont be called the Standing Pond amphibolite. The locality name was taken from Standing Pond, 10 miles northwest of Hanover, New Hampshire. Inasmuch as the grade of metamorphism changes along the strike and the amphibolites change into chlorite schists, the unit was subsequently called the Standing Pond volcanics (Billings et al., 1952, p. 39).

Distribution. In New Hampshire the Standing Pond volcanics are confined to a small area 4 miles west of Claremont.

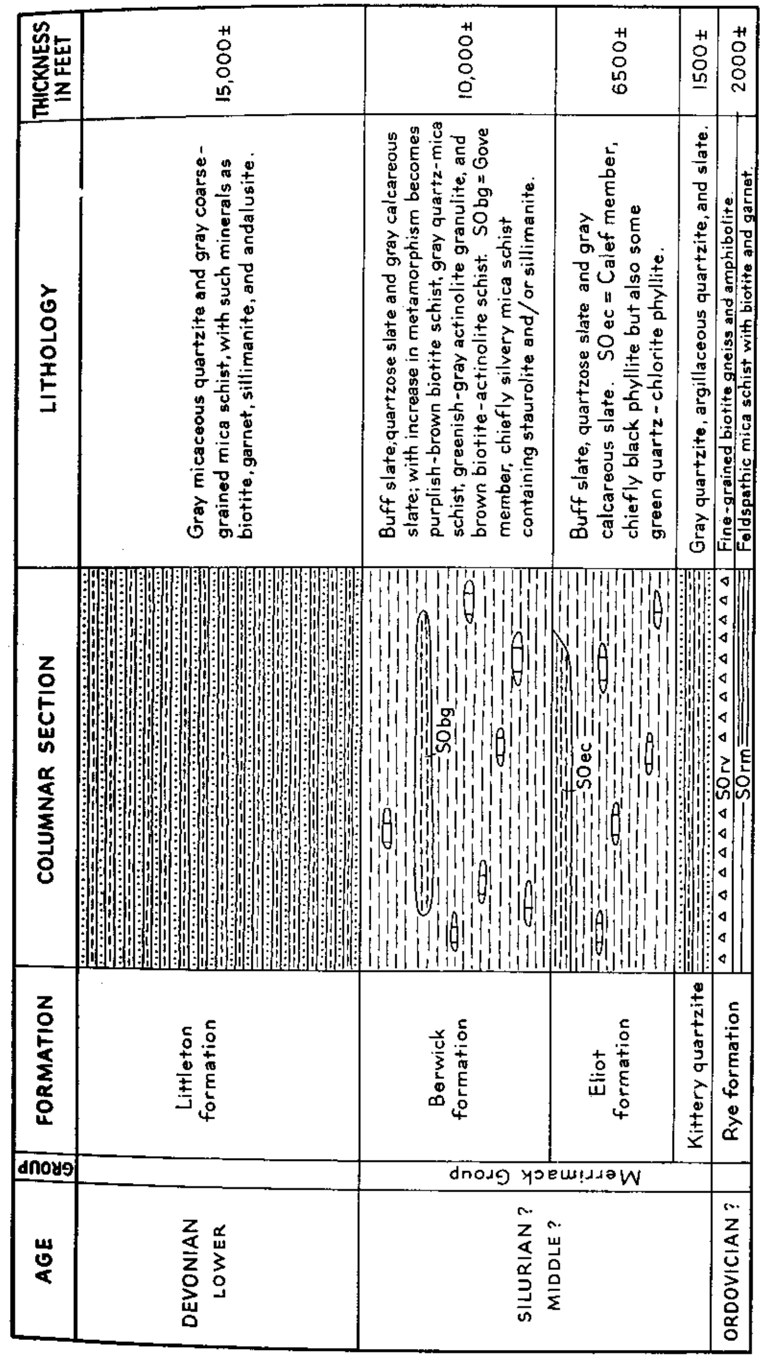

Figure 4. Stratigraphic sequence in southeastern New Hampshire.

Lithology. In New Hampshire the Standing Pond volcanics consists of green chlorite schists and white schistose soda-rhyolite. Inasmuch as the chlorite schists have essentially the composition of andesite and basalt, and because of the soda-rhyolites, the formation is considered to be of volcanic origin. Because in places the beds are only a few inches thick, the formation is considered to represent pyroclastic rocks rather than flows.

Thickness. In eastern Vermont the formation is about 1,000 feet thick (Billings et al, 1952, p. 39).

Correlation. The volcanic rocks 4 miles west of Claremont can be traced continuously to the type locality northwest of Hanover (Billings et al, Plate 4). On the geological map this formation is assigned to the Middle Ordovician (?). It is possibly Silurian or Lower Devonian.

Gile Mountain Formation

Name. Doll (1944, p. 18) proposed the name Gile Mountain schist for a group of gray metamorphosed argillaceous and arenaceous rocks in the Strafford quadrangle in east-central Vermont. The locality name was chosen from Gile Mountain, six miles north-northwest of Hanover, New Hampshire. Although the rocks may properly be called schists in the type locality, inasmuch as the character of the rocks changes because of differences in grades of metamorphism, this stratigraphic unit is now called the Gile Mountain formation (White and Jahns, 1950, p. 188; Billings et al, 1952, p. 39).

Distribution. This formation is found in four areas in New Hampshire. One is a small band ¼ mile wide, 1½ miles west of Claremont. A second area covers 12 square miles east of the Connecticut River around Plainfield. A third area is along the Connecticut River 6 miles west of Littleton. The fourth and much the largest area lies east of the Connecticut River in Coös County. This area, more than 40 miles long and as much as 6 miles wide, has never been studied in detail. The Standing Pond volcanics, which lie between the Waits River formation and the Gile Mountain formation in east-central and southern-central Vermont, are absent here.

Lithology. The Gile Mountain formation in New Hampshire is composed chiefly of dark-gray slate, dark-gray phyllite, gray arenaceous phyllite, and quartz-sericite schist. Locally,

porphyroblasts of biotite are present. The rocks, originally shales and argillaceous sandstones, are in beds an inch to many feet thick. Detailed petrographic work has not been done on the formation in Coös County.

Thickness. In eastern Vermont the Gile Mountain formation may be as much as 5,000 feet thick (Billings et al, 1952, p. 39). In Coös County it likewise appears to have a similar thickness along the Connecticut River, but cannot exceed 2,500 feet in the band that lies east of the Waits River limestone. Likewise, in the band 1½ miles west of Claremont, it cannot be more than 2,000 feet thick.

Correlation. All four areas of the Gile Mountain formation in New Hampshire can be traced continuously to the type locality northwest of Hanover. On the geological map it is shown as Middle Ordovician (?). It may be Lower Devonian.

Meetinghouse Slate

Name. Doll (1944, p. 19) proposed that a band of slate in the Strafford quadrangle in eastern Vermont be designated the Meetinghouse slate, but he classified it as the uppermost member of the Gile Mountain formation. White and Jahns (1950, p. 190) and White and Billings (1951, p. 656) raised this unit to formation rank. This usage has been adopted in this report. The locality name is from Meetinghouse Hill, which lies four miles northwest of Hanover, New Hampshire.

Distribution. In New Hampshire a small band of slate two miles long just east of the Connecticut River north of Plainfield has been mapped as Meetinghouse slate.

Lithology. In New Hampshire the Meetinghouse slate is a dark-gray slate with thin beds of gray quartzite.

Thickness. In eastern Vermont the Meetinghouse slate is estimated to be about 1,100 to 2,500 feet thick (Doll, 1944, p. 19; White and Billings, 1951, p. 651). North of Plainfield it is about 1,100 feet thick (Lyons, 1955, p. 112).

Correlation. The Meetinghouse slate 4 miles north of Plainfield is continuous with the formation at the type locality. Elsewhere in New Hampshire the Meetinghouse slate has not been shown between the Gile Mountain formation and the Orfordville formation. The Meetinghouse slate has not been mapped in Coös

County between the Gile Mountain and Orfordville formations. This is either because the formation is absent or it has been mapped with the Orfordville formation.

On the geological map the Meetinghouse slate has been classified as Middle Ordovician (?). It may possibly be Lower Devonian.

Orfordville Formation

Name. Hadley (1939; 1942, p. 119) proposed that a group of dark-gray schists and metamorphosed volcanics in the Mt. Cube quadrangle be called the Orfordville formation, from the village of that name 16 miles north-northeast of Hanover.

Distribution. The Orfordville formation is exposed in western and northern New Hampshire. One belt, east of the Connecticut River, can be followed for 55 miles from North Charlestown to north of Pike. The formation reappears around Charlestown. Two small areas appear along the Connecticut River in the southwestern part of the state; one lies 2 miles north of West Chesterfield, the other is 2 miles southwest of West Chesterfield. In the northern part of the state a fourth and very large area, 36 miles long as much as 10 miles wide, extends northeasterly from Simms Stream through the Connecticut Lakes to the Canadian border.

Lithology. This is one of the most complex formations in New Hampshire. There are two principal reasons for this. The formation initially consisted of a complex assemblage of volcanic and sedimentary rocks. Secondly, the formation, because it has undergone differing grades of metamorphism, is found in the chlorite, biotite, garnet, and staurolite zones. Some representative estimated modes are given in Table 1.

Between Orford and Hanover much of the formation consists of dark-gray mica schist that in many places contains porphyroblasts of garnet, staurolite, and, locally, kyanite. But volcanic rocks constitute an important part of the formation. In places they are so thin that they have not been distinguished from the mica schist on the geological map. Locally, they are of a sufficient magnitude to map separately. One of these bands has been called the Sunday Mountain volcanics. The name comes from Sunday Mountain, 1½ miles north-northeast of Orfordville. This member, which is 0 to 400 feet thick, lies at the top of the Orfordville formation. Between Orfordville and Pike the Sunday Mountain volcanics in this belt consist of interbedded, fine-grained gray biotite gneiss and black to dark-green amphibolite. The gneiss is metamorphosed soda-rhyolite, whereas the amphibolite is metamorphosed andesite and basalt. The volcanics are believed to be chiefly of pyroclastic origin, because the different lithological types alternate in beds that are only a few inches thick. Another volcanic member has been designated the Post Pond volcanics, from Post Pond, one mile north of the village of Lyme (Hadley, 1939; 1942). It consists of amphibolite and fine-grained biotite gneiss. Lyons (1955, p. 116) has shown that this member is near the top of the Orfordville formation. The Post Pond volcanics reach a maximum thickness of 4,000 feet, but toward the north they pinch out.

The Hardy Hill quartzite, named from Hardy Hill, 2 miles northeast of Lebanon (C. A. Chapman, 1939, p. 132-133) is a gray to white quartzite and quartz conglomerate, with minor amounts of quartz-mica schist and mica schist. The pebbles in the conglomerates are vein quartz and quartzite. The Hardy Hill quartzite is 0 to 250 feet thick.

Calcareous rocks in the Orfordville formation, 1 mile north-northeast and 1½ miles south-southeast of Plainfield, are not separately shown on the geological map. Forming small lentils not over 100 feet thick, they are composed of gray quartz-calcite schist and white marble (Lyons, 1955, p. 113).

In the metasomatized zone around the Lebanon granite the Orfordville formation has been altered to a gray feldspathic gneiss (Lyons, 1955, p. 114).

The Orfordville formation plunges northward under the Albee formation in the vicinity of Piermont and Pike. From Hanover the Orfordville may be traced southward to North Charlestown where it is cut off by the Littleton formation, but the stratigraphic and structural relations here have not yet been satisfactorily resolved, and more field work is necessary. Throughout this belt the Orfordville has the lithologic features described above except that, because of a decrease in the grade of metamorphism, staurolite and garnet disappear; hence, most of the rocks are in the biotite zone.

Three small areas of Orfordville formation are shown further south just east of the Connecticut River. One is between Charlestown and East Walpole; a second is 4 miles west-southwest of Westmoreland; and a third is 4 miles west of Chesterfield. In these areas, the Orfordville is chiefly phyllite. Where the grade of metamorphism is sufficiently high, the formation contains biotite and garnet porphyroblasts.

From Haverhill southward to Plainfield small patches of the Orfordville formation northwest of the Ammonoosuc thrust (see structure map accompanying the geological map) lie east of the Connecticut River. They are all in the chlorite zone. The most complete section is 4 miles southwest of Haverhill (White and Billings, 1951, p. 657). Here the main part of the formation consists of dark-gray slate and gray arenaceous slate, but includes some chlorite schist and schistose soda-rhyolite. The Sunday Mountain volcanics at the top of the formation are chiefly gray to white slaty soda-rhyolite tuff; this unit is 200 feet thick. The Hardy Hill quartzite is a buff to gray quartz conglomerate 30 feet thick.

The belt of the Orfordville formation in Coös County, extending for more than 30 miles north-northeast of Simms Stream, has not been studied in detail. Because of a lack of detailed information, no attempt has been made on the geological map to distinguish metasedimentary rocks from metavolcanics. The following description is based largely on reconnaissance work by Billings and Heald in 1951. For a mile east of Pittsburg the rocks show characteristic Gile Mountain lithology; that is, the rocks are interbedded dark-gray slate and gray micaceous quartzite. The rocks further east have been assigned to the Orfordville formation. The northwestern half of the belt of rocks mapped as Orfordville is exposed in a band 4 miles wide. These rocks can be studied along Route 3 between Pittsburg and the Canadian border north of Third Lake. The principal rocks are: (1) green chlorite-epidote-actinolite schist; (2) chlorite schist; (3) white to buff feldspar-quartz-sericite schist; (4) gray micaceous quartzite; and (5) gray phyllite. The first two are metamorphosed mafic volcanic rocks, the third is a metamorphosed soda-rhyolite, and the last two are metamorphosed sediments.

The most southeasterly part of the band mapped as Orfordville is exposed 1 mile west of Dixville Notch on the south flank of Abeniki Mountain. The rock is a medium-grained black amphibolite. Little is known about the rest of this southeastern half of the band of Orfordville; the boundary between the Orfordville and the Albee formations has been assumed to be the same as the southeastern boundary of Hitchcock's Lyman group (Hitchcock, 1878).

Thickness. Hadley (1942, p. 119) estimated the Orfordville formation to be about 5,000 feet thick in the type locality, but the base was not exposed in that region. Lyons (1955) estimated the thickness as 5500 to 6000 feet.

Correlation. The various areas mapped as Orfordville are isolated from one another, hence the correlation is not entirely satisfactory. The belt that extends southward for more than 50 miles from Pike to North Charlestown, includes the type locality; these rocks plunge northward beneath the Albee formation north of Orfordville. The area 4 miles southwest of Haverhill, although it is separated by the Ammonoosuc thrust (see structure map) from the belt that includes the type locality, is assigned to the Orfordville formation for several reasons. It was originally lithologically similar to the type Orfordville, although it is no longer similar because of the differences in the grade of metamorphism. The various members appear in appropriate stratigraphic position: the Sunday Mountain volcanics at the top and the Hardy Hill quartzite in the middle. Moreover, this area southwest of Haverhill plunges northward beneath the Albee formation, just as the Orfordville in the type area.

The correlation of the rocks mapped around Charlestown and further south is on a less secure basis. They are cut off from the main belt by an area of Silurian and Devonian.

The area in Coös County is correlated with the Orfordville formation for several reasons. It is lithologically like the low-grade Orfordville. Moreover, it occupies the stratigraphic position of the Orfordville. It lies directly west of and presumably underneath the Albee formation. It lies east of and apparently above the Waits River and Gile Mountain formations.

The Orfordville is pre-Silurian. Although shown as Middle Ordovician (?) on the geological map, it may be somewhat older.

Albee Formation

Name. The Albee formation was named from Albee Hill on the north end of Gardner Mountain, 8 miles west of Littleton (Billings, 1934, 1935, 1937).

Distribution. The Albee formation is confined to the northern part of the state. The type area is part of a band that is over 40 miles long. From Albee Hill the formation may be followed continuously southward through New Hampshire and eastern

Vermont to the vicinity of Haverhill, where the Albee disappears because of the northward plunge of the folds. Northeastward from Albee Hill the formation may be followed through eastern Vermont and western New Hampshire to 3 miles north of Whitefield. Large, isolated inclusions in the Highlandcroft plutonic series continue the formation at least 8 miles further northeast.

A second large area extends northeasterly from Northumberland to the Maine border. This band is 40 miles long and as much as 18 miles wide. This is actually a continuation of the belt that contains the type locality, but it is interrupted for a few miles by the Highlandcroft plutonic series.

A third belt of the Albee formation extends north-northeast from near Orfordville for 25 miles to north of Lisbon. Isolated patches of the formation appear for 15 miles to the northeast.

Lithology. The Albee formation appears in all five metamorphic zones. Consequently it shows considerable variation in lithology. Where least metamorphosed, that is, where it is in the chlorite zone, it consists primarily of slate, phyllite, feldspathic phyllite, quartzose phyllite, argillaceous quartzite, quartzite and feldspathic quartzite. Many of these rocks are yellowish green, a feature that distinguishes this unit from the other formations in New Hampshire. Some of the quartzites are white, whereas some of the phyllites are black or dark-green. In the biotite zone, the rocks are similar except that they may contain biotite porphyroblasts. In the garnet and staurolite zones, the rocks become light-gray to white micaceous quartzite, gray quartz-mica schist, and gray mica schist. These rocks, especially the schists, may contain porphyroblasts of biotite, garnet, or staurolite. The Albee formation is found in the sillimanite zone only around the French Pond granite at North Haverhill. Here the Albee consists of white to light-gray micaceous quartzite and coarse-grained mica schist with needles of sillimanite that can be recognized only under the microscope. The Piermont member of the Albee formation (Hadley, 1942, p. 126) is confined to an area around Piermont. It lies in the staurolite metamorphic zone, hence such minerals as biotite, garnet, and staurolite are present. Whereas the Albee formation consists chiefly of light-colored rocks, the Piermont member also contains gray to dark-gray mica schists with porphyroblasts of biotite, garnet and/or staurolite. Some representative estimated modes of the Albee formation are given in Table

2; only the chlorite, staurolite, and sillimanite zones are included in the table, because the modern publications do not cover those areas where the formation is in the biotite and garnet zones.

Thickness. The Albee formation is approximately 5,000 feet thick (Hadley, 1942; White and Billings, 1951), but a precise figure is difficult to obtain because of the extensive folding to which the formation has been subjected.

Correlation. The area that includes the type locality is essentially a single belt that extends from Piermont on the southwest to the Maine border on the northwest, a distance of 90 miles. The belt that extends for 25 miles on the southeast side of the Ammonoosuc thrust from near Orfordville to north of Lisbon is correlated partly because of its lithology. Moreover, it is one stratigraphic unit in a sequence that contains seven formations that can be correlated with the sequence on the northwestern side of the Ammonoosuc thrust. The isolated areas that are found for 15 miles to the northeast are correlated primarily on lithology, but also because they are associated with Ammonoosuc volcanics. Although the Albee formation is shown on the geological map as Upper Ordovician (?), it may be Middle Ordovician or slightly older.

Ammonoosuc Volcanics

Name. The locality name has been taken from the old Ammonoosuc mining district of Hitchcock (1878) northwest of the Ammonoosuc River between Woodsville and Littleton (Billings, 1934, 1935, 1937).

Distribution. The Ammonoosuc volcanics are found in four belts, chiefly in the western part of the state. One, that includes the type locality, extends for 22 miles from Woodsville on the southwest to 5 miles west of Whitefield on the northeast. A second area, 5 miles long, is just east of the Connecticut River northeast of Monroe. A third belt extends for 26 miles from 3 miles east of Haverhill on the southwest to 3 miles west of Whitefield on the northeast. The fourth band, although locally interrupted, extends the entire length of the state for 150 miles from the Massachusetts state line south of Winchester to the Maine border northeast of Berlin.

Lithology. In the two areas northwest of the Ammonoosuc River the Ammonoosuc formation is in the chlorite zone. There are three principal kinds of rocks. (1) One consists of dark-green chlorite and chlorite-epidote schists, some of which are conglomeratic. (2) A second group consists of buff to white soda-rhyolite that is massive to schistose; some of these rocks have conspicuous quartz and albite crystals up to 1/8 inch in diameter; some of the soda-rhyolite is volcanic conglomerate. (3) A third group consists of dark slate and impure gray quartzite. Some representative estimated modes are given in Table 3.

The pebbles in the soda-rhyolite volcanic conglomerate average 4 inches in diameter, but reach a maximum length of 12 inches. Many are tectonically elongated. The most common boulders are soda-rhyolite, generally with phenocrysts of quartz and albite-oligoclase. Many of the soda-rhyolites are pyroclastic rocks, because some are bedded, others form the matrix of the conglomerates. Some of the massive soda-rhyolite may be in lava flows.

Some of the chlorite and chlorite-epidote schist is bedded, hence presumably represents pyroclastic material. Although chlorite is the characteristic dark mineral in these rocks, actinolite is abundant in some. Metamorphosed sedimentary rocks, constituting 10% to 15% of the formation, are black slate, dark-gray arenaceous slate, and gray impure quartzite. Sedimentary rocks are especially abundant in the area 3 miles northwest of Littleton.

Most of the Ammonoosuc formation is of volcanic origin, a fact first established by F. H. Lahee (1916). The chemistry, mineralogy, and texture of the soda-rhyolites demonstrates their volcanic origin; the more massive porphyritic types are obviously rhyolites. The chlorite and chlorite-epidote schists, although now lacking volcanic textures, have the chemical composition of andesites and basalts. The bedding, as well as the conglomeratic and fragmental textures, indicate that most of the formation is of pyroclastic origin rather than flows.

Ammonoosuc volcanics in the biotite zone are confined to a small area near Monroe. The rocks are similar to those in the chlorite zone, except that biotite porphyroblasts are present. The Ammonoosuc volcanics north of Milan are assigned to the garnet zone, but these rocks have not been studied in detail.

The Ammonoosuc formation in the band along the Ammonoosuc River and in the belt 150 miles long extending from Massachusetts to Maine is mostly in the staurolite and sillimanite zones. The mafic rocks, originally andesite and basalts, are massive to schistose dark-green amphibolites composed of hornblende and andesine. The siliceous rocks, originally soda-rhyolites, are fine-grained gray biotite gneiss composed of quartz, sodic oligoclase, a little biotite and, in some specimens, microline. The metamorphosed sedimentary rocks are black pyritiferous biotite schists.

Thickness. In the areas southwest of Littleton, where both the top and bottom of the formation are present, the Ammonoosuc volcanics are about 2,000 feet thick, but extensive folding makes a precise determination of the thickness difficult. In the long belt that extends north from Massachusetts to Maine, the formation is usually much thinner because only the top is exposed above the Oliverian plutonic series. But 4 miles southwest of Randolph the thickness is about 5,000 feet (Billings, 1941, p. 877).

Correlation. The belt of the Ammonoosuc volcanics that extends northeast from Woodsville includes the type locality. The second belt northeast of Monroe is correlated with the Ammonoosuc volcanics because of its lithology and stratigraphic position above the Albee formation. The third belt, extending northeast from 3 miles east of Haverhill, is correlated because of its lithology and the repetition of the entire stratigraphic sequence from the Albee to the Littleton. Similarly, the fourth belt, extending the whole length of the state, is correlated because of its lithology and the repetition of the stratigraphic sequence, from the Ammonoosuc formation through the Littleton formation.

Although the Ammonoosuc volcanics are assigned to the Upper Ordovician (?) on the geological map, the formation may be Middle Ordovician.

Partridge Formation

Name. This formation was named from Partridge Lake, 5½ miles west of Littleton (Billings, 1934, 1935). Exposures of the formation are found north and south of the lake.

Distribution. The Partridge formation is confined to two general areas. One is in the vicinity of the Ammonoosuc River, between Bath and Littleton. The second area is in the southwestern part of the state south of Claremont.

There are four separate areas in the region around Bath and Littleton. One is the type locality 6 miles west of Littleton. A second is 9 miles west-southwest of Littleton. The southwestern end of a third area is 3 miles west of Bath. A fourth area is 2½ miles east of Bath.

In the region south of Claremont there are several large areas occupied by the Partridge formation, as well as several smaller areas. One relatively large arcuate area lies east of Alstead. A second area, shown as 6 miles long, lies 4 miles north of Keene; because of the scale of the map, the narrow southward continuation of this belt, which is east of Keene and extends nearly to the Massachusetts border, could not be shown. A third arcuate area, which extends southwest from north of Surry, is shown as ending 2½ miles north of Chesterfield; this belt actually continues eastward through and beyond Spofford, but could not be shown because of the scale of the map. Four small areas of the Partridge formation are shown 6 miles west-northwest of Keene.

Lithology. In the three areas northwest of the Ammonoosuc River between Bath and Littleton, the Partridge formation is in the chlorite zone of metamorphism. The rock is chiefly a dark-gray slate. At the base, thin-bedded light-gray quartzite and buff soda-rhyolite tuff are interbedded with dark-gray slate. This basal unit is 25 feet thick.

In the area east of Bath and the several areas west of Keene, the Partridge is in the staurolite zone; the rocks are mica schist, garnet schist, and, locally, garnet-staurolite schist. In the area north of Keene, and in the area east of Alstead, the formation is in the sillimanite zone; the rocks are mica schist, garnet schist, and, locally, sillimanite schist.

Thickness. In the area northwest and southeast of the Ammonoosuc River between Bath and Littleton, the Partridge formation reaches a maximum thickness of about 2,000 feet, but is absent in many places between the Ammonoosuc volcanics and the Silurian formations because of the unconformity at the base of the Silurian. Between Franconia and Claremont, a distance of 75 miles, the Partridge formation is not present between the Ammonoosuc and Silurian formations, presumably because of the same unconformity. In the area east of Alstead the formation is 500 to 2,000 feet thick. Ten miles west of Keene the formation is 1,000 feet thick but thins easterly so that 1 mile east of Keene it is only 75 feet thick; still further south it pinches out and is absent at the Massachusetts line (Moore, 1949).

Correlation. The three areas northwest of the Ammonoosuc River are correlated with one another because they are lithologically similar and overlie the Ammonoosuc volcanics; the distinctive basal unit is present in each of the three areas. The slate east of Bath is correlated with the Partridge because it was originally lithologically identical with the rock in the type area; moreover, it occupies the same stratigraphic position above the Ammonoosuc volcanics and beneath the Silurian formations.

A distance of nearly 60 miles separates the most southerly exposures of the Partridge formation in the vicinity of the Ammonoosuc River from the most northerly exposures south of Claremont. In both areas these rocks, which were originally shales, occupy the same stratigraphic position above the Ammonoosuc volcanics and beneath the Clough quartzite.

The Partridge formation is shown on the geological map as Upper Ordovician (?), but it may be Middle Ordovician.

Silurian

Clough Quartzite

Name. The name for this formation was taken from Clough Hill, 2 miles northwest of Lisbon (Billings, 1934, 1935, 1937). In the earlier papers, it was called Clough conglomerate, but, inasmuch as quartzite is much more common in the formation than conglomerate, the name was later changed to Clough quartzite.

Distribution. The Clough quartzite is confined to several belts in the western part of the state, extending from 5 miles south of Littleton to the Massachusetts state line. These belts are generally narrow and are somewhat more discontinuous than shown on the geological map; because of the scale, it was impossible to show some of the gaps in the formation.

The most westerly belt, about 4 miles long, is 3 miles west of Lisbon. A second band, likewise about 4 miles long, is 1 mile east of Lisbon. A third belt has its northeasterly limit 3 miles west of Franconia. From here it may be followed south-southwesterly, with occasional offsets and minor branches, for 75 miles to a locality 8 miles south of Claremont. A few isolated areas of the Clough quartzite lie east of this belt: one, five miles long, is 3 miles west of the summit of Mt. Moosilauke; a second, 4 miles long, is 4 miles east of the south end of Mascoma Lake; and a third is 5 miles east of Claremont.

The disappearance of the Clough at the south end of this long belt is because of the southerly plunge of an anticline in the vicinity of Acworth. Four miles further south the Clough reappears because of the northerly plunge of the anticline. Several separate areas appear south of here. (1) A belt near South Acworth is a discontinuous horseshoe that opens south; the western branch extends 4 miles to the south, whereas the eastern branch extends 5 miles to the south. (2) The eastern branch reappears 6 miles further south, that is, 6 miles north of Keene; from here it may be traced 16 miles to the south. (3) The western half of the horseshoe reappears 9 miles north-northwest of Keene, extends southwest for 12 miles, whence it trends east through Spofford for 10 miles; an isolated patch lies 6 miles west-northwest of Keene. (4) Another isolated horseshoe-shaped mass lies a few miles north of Hinsdale. (5) Seven isolated bodies lie north, southwest, and southeast of Winchester.

Lithology. The Clough formation is relatively uniform in all the various belts, except that with increasing metamorphism it gets coarser grained and the pebbles become more obscure. Because of its resistance, it generally stands out in bold, conspicuous outcrops. In fact, some of the higher mountains of western New Hampshire are held up by this formation: (1) Black Mountain, Sugarloaf and Hogsback, all three of which are west of Mt. Moosilauke; (2) Piermont Mountain and Mt. Cube, respectively 7 miles northeast and 6 miles east of Orford; (3) Holts Ledge, 3 miles south of Lyme; (4) parts of Moose Mountain, 7 miles east of Hanover; (5) Croydon Mountain, 8 miles northeast of Claremont; (6) Green Mountain, 4 miles northeast of Claremont; and (7) Perry Mountain, 8 miles south of Claremont.

The most common rock is very pure quartzite, which generally is white, but in the area northwest of Lisbon may be locally gray because of small amounts of argillaceous material. In the area east of the Ammonoosuc River and in the belt extending south to the southwest corner of the state, the rock is somewhat more coarsely crystalline than northwest of the river.

Conglomerates are locally conspicuous. The pebbles, although locally spherical, are, in many places, ellipsoidal because of tectonic elongation. North of latitude 44° N. the pebbles are commonly 1″ to 3″ long. In the southern part of the area the

pebbles are 1″ to 12″ long; the longest axis of a pebble may be as much as 10 times as long as the shortest. The pebbles are chiefly vein quartz, but a few are quartzite, green schist, or soda-rhyolite.

In the belt southeast of the Ammonoosuc River and extending south to the Massachusetts border, mica schists are locally present. They are generally white quartz-muscovite schist with minor amounts of biotite, garnet, and/or staurolite. Small amounts of sillimanite are present in some of these mica schists in the sillimanite zone.

Thickness. The Clough quartzite is absent northeast of a line extending westward from Franconia to Lyman, presumably because it was not deposited. The Clough was laid down in a sea transgressing from the southwest. At the end of Clough time the shoreline was approximately at the position of the present northeast limit of the formation. Further north, the Fitch formation, to be described in a later section, rests directly on the older formations. South of Franconia the Clough becomes progressively thicker. North of latitude 44° N. the most reliable measurements indicate that the formation is not over 150 feet thick. The formation is probably repeated by folding 2 miles south of the Wild Ammonoosuc River, where the breadth of outcrop is 3,000 feet. In the area 6 miles east of Lyme, Hadley (1942, p. 130) says that the thickness ranges from 400 to 1,200 feet. In the area 6 miles east of Lebanon, Chapman (1939, p. 139) says the thickness ranges from 200 to 1,200 feet. Still further south, the formation is considerably thinner. Six miles east-northeast of Charlestown, the Clough is 300 feet thick. South of latitude 43° N. the thickness is generally less than 200 feet, and in many places the formation is absent. One mile east of the Connecticut River, on the east side of Wantastiquet Mountain, the Clough is 925 feet thick (Moore, 1949, p. 1629). The formation apparently thins to the east, because 17 miles to the east, near Marlboro, it is only 100 feet thick. Still further south, in the Mt. Grace area of Massachusetts, Hadley (1950) gives the maximum thickness of the Clough as 100 feet.

Correlation. The correlation of the Clough quartzite north of latitude 43° 45′ presents no problems. In these areas the Clough directly underlies the distinctive Fitch formation and overlies the Ammonoosuc and Partridge formations. The correlation still further south, as far as 8 miles south of Claremont, is equally satisfactory, inasmuch as the formation can be traced continuously, and is locally overlain by the Fitch formation. But 8 miles south of Claremont, the Clough plunges beneath the surface on the nose of an anticline. The Partridge formation that is present at this place between the Ammonoosuc and Clough formations is too narrow to appear on the geological map.

Four miles further south, 2 miles west of South Acworth, quartzites reappear on the nose of a northerly plunging anticline. These quartzites are correlated with the Clough formation because of: (1) lithology; (2) thickness; and (3) a position in a stratigraphic sequence that begins at the base with the rocks of the Oliverian plutonic series and passes upward through the Ammonoosuc volcanics, Partridge formation, Clough quartzite, and Littleton formation. Although there are some breaks in the continuity, the Clough on the west side of the anticline can be followed southwest and then east to east of Spofford. The Clough on the east flank can be followed east of Keene and further south almost to the Massachusetts border.

The Clough north of Hinsdale and the isolated bodies in southwestern New Hampshire are correlated on the same basis: (1) lithology; (2) thickness; and (3) position in a stratigraphic sequence.

The Clough quartzite is considered to be Lower or Middle Silurian because it immediately underlies and is transitional upward into the fossiliferous Middle Silurian Fitch formation.

Fitch Formation

Name. This formation is so named because of the classic fossil locality near Fitch Hill, 2 miles west-northwest of Littleton (Billings, 1934, 1935, 1937). Fitch Hill is a small knoll on the north end of Walker Mountain (Lahee, 1912). In 1933 the property on which the fossil locality is located was owned by G. E. Fitch.

Distribution. The Fitch formation is confined to western New Hampshire, from the vicinity of Littleton south to a point 2 miles north of Acworth. The distribution is similar to that of the Clough formation. However, between Acworth and Hanover Center the Fitch is discontinuous. Hence, it is not present everywhere between the Clough and the Littleton formations. But the

Fitch formation extends northeasterly beyond the northeast limit of the Clough in the vicinity of Franconia and Lyman.

The most westerly belt, extending from 2 miles north of Bath in a northeasterly direction 2 miles west of the Ammonoosuc River, terminates 3 miles north of Littleton. The second belt, which extends in a northeasterly direction from a mile west of Landaff, ends 3 miles south of Littleton. A third belt, that has its southern terminus 4 miles south of Lyme, extends north almost to Franconia, where it trends northwest for a mile, then southwest for 4 miles. Four miles west-northwest of Whitefield small patches of the Fitch formation are preserved between the Littleton and the older formations, but they are too small to show on the geologic map.

Lithology. The Fitch is a calcareous formation that consists in part of limestone, marble, and, in the higher metamorphic zones, actinolite and diopside granulites. Representative estimated modes are given in Table 4.

Northwest of the Ammonoosuc River, where the formation is in the chlorite metamorphic zone, the rocks are bluish-gray limestone, white marble, buff dolomitic slate, gray calcareous slate, and gray slate. Less common rocks are white calcareous sandstone, gray arenaceous limestone, white arkose, and light-gray quartz conglomerate. The arkose and quartz conglomerate are most abundant in the northern part of this belt. The various rocks are interbedded. The gray slate is as much as 170 feet thick, as is also the buff dolomitic slate. The gray calcareous slate is as much as 150 feet thick. The bluish-gray limestone and white marble are locally 35 feet thick, but generally they are much thinner. The gray arenaceous limestone and the white calcareous sandstone do not exceed 15 feet in thickness. The white arkoses are as much as 50 feet thick west of Littleton. The quartz conglomerates do not exceed 6 feet in thickness.

Elsewhere, the Fitch formation is in the staurolite metamorphic zone. The rocks are white to buff marble, greenish-gray diopside-actinolite granulite, greenish-gray actinolite marble, purplish-brown actinolite-biotite schist, purplish-brown biotite-calcite schist, light-gray arenaceous marble, white quartzite, and light-gray mica schist. Hadley (1942, p. 133) says that in the Mt. Cube area the light-gray mica schists are most abundant. They consist chiefly of quartz and biotite, with minor amounts of muscovite and calcite; pods of buff marble a few inches thick are common. Although marble beds are as much as 4 feet thick, they constitute a small part of the formation. Quartzite beds attain a maximum thickness of some tens of feet. The other rocks, although conspicuous where present, never exceed a few feet in thickness. Three miles west of Newport, amphibolites have been assigned by C. A. Chapman (1952) to the Fitch formation.

South of Hanover Center, marbles are absent from the Fitch formation. It consists mostly of mica schist and the distinctive lime-silicate granulites containing actinolite and diopside.

Thickness. The Fitch is a thin formation. Northwest of the Ammonoosuc River (Billings, 1937, p. 481-485) the thickness 7½ miles southwest of Littleton is 769 feet. In this belt the formation thins northeasterly. Four miles west of Littleton it is not over 490 feet, and 2½ miles north of Littleton it is only 300 feet thick. Five miles northeast of Littleton it is only a few tens of feet thick, and 8 miles to the northeast it is absent.

In the band that extends southwest from Franconia, Hadley (1942, p. 133) says that in the Mt. Cube area the thickness ranges from 400 to 600 feet. Further south, the formation pinches out but reappears in the Sunapee quadrangle (C. A. Chapman, 1952, p. 386); 6 miles north of Newport it is not over 200 feet thick, but 3½ miles west of Newport it may be as much as 800 feet thick. South of Acworth the Fitch formation is not present between the Clough and Littleton formations.

Although the contact of the Ammonoosuc and Littleton formations may be traced for 25 miles from 5 miles north of Bretton Woods to the Maine border north of Mt. Success, the Fitch formation has not been observed. Just as the Clough formation pinches out along a line connecting Franconia and Lyman, similarly the Fitch apparently pinches out along a line connecting Whitefield and Twin Mountain. Inasmuch as the Fitch overlaps the Clough formation, it appears that the shore of a transgressing Silurian sea had reached the line joining Franconia and Lyman by early Middle Silurian time, but, by the middle of the Middle Silurian it had reached the line joining Whitefield and Twin Mountain.

Correlation. The correlation of the Fitch formation southeast of the Ammonoosuc River with the type area northwest of the river, is based on several lines of evidence: (1) lithologic similarity (in terms of the rocks prior to metamorphism); (2) thickness; and (3) position in a stratigraphic sequence extending from the Ammonoosuc to the Littleton formation. Moreover, as shown in a later section, there are also some paleontological data. The largest band can be followed continuously southwest from Franconia to Hanover Center. Although the Fitch is discontinuous south of here, the stratigraphic position and lithology suffice to correlate the isolated patches.

Devonian

Littleton Formation

Name. The locality name for this formation was proposed by C. P. Ross (1923) from the exposures on Walker Mountain 2½ miles west-southwest of Littleton.

Distribution. This is the most widespread of all the formations in New Hampshire and occupies a large area extending north-northeasterly from Massachusetts to Maine.

The type locality is a band 10 miles long that lies northwest of the Ammonoosuc River between Lisbon and Littleton. Two additional areas on this trend lie 2 miles north and 8 miles northeast of Littleton. A second band, 8 miles long, extends from Landaff to a point 3 miles northwest of Franconia. A third band can be followed from 2 miles west of Franconia in a southwesterly direction for 8 miles. This band reappears 3 miles southwest of Benton, whence it may be followed to the southwest corner of the state, a distance of nearly 100 miles. The fourth and by far the largest area occupies the Merrimack synclinorium. On the structure map accompanying the geological map, this synclinorium is separated from the Bronson Hill anticline on the northwest by a heavy line and, similarly, is separated from the Fitchburg pluton on the southeast by another heavy line. Along the Massachusetts boundary this band of the Littleton formation is 22 miles wide. The eastern boundary is 4 miles southwest of Mason. This broad band trends north-northeasterly across the state, interrupted in many places by large and small bodies of plutonic rocks. The distance across the band along the Maine-New Hampshire border is 84 miles, but this great distance is because the state border is diagonal to the trend of the band. The northwestern boundary crosses the Maine border 8 miles east-northeast of Berlin, whereas the southeast boundary crosses into Maine 6 miles north of Dover. This band of the Littleton formation in central New Hampshire is nearly 60 miles wide. In extreme southwestern New Hampshire, several small areas of the Littleton formation lie north, east, and southwest of Winchester.

Lithology. As shown by the explanation accompanying the geological map, the lithology of this formation is very complex. This is partly because the formation, originally composed chiefly of argillaceous and arenaceous sediments, contained beds of other rocks, notably volcanics, quartzites, and impure dolomites. Secondly, the formation shows a great range in grade of metamorphism, from the chlorite zone to the sillimanite zone. Thirdly, because the formation is locally intricately intruded by numerous bodies of plutonic rocks, some areas must be mapped as mixtures of the metamorphosed sedimentary rocks and the plutonic rocks. Representative estimated modes are given in Table 5. Modes are not given for the metamorphosed volcanic rocks, inasmuch as they are similar to those in the Ammonoosuc volcanics.

The areas of the Littleton formation northwest of the Ammonoosuc River, between Lisbon and Whitefield, are in the chlorite zone of metamorphism. The most abundant rocks are dark-gray slate and dark-gray sandstone. Although in places these rocks alternate in beds an inch to a foot thick, locally one of them constitutes many hundreds of feet of the formation. The lowest 1,000 feet of the formation is exclusively black slate. Above this, a zone of black slate and volcanics, described below, is 700 to 900 feet thick. Still higher are massive dark-gray sandstones about 500 feet thick. The uppermost 3,000 to 4,000 feet of the formation consists of interbedded dark-gray slate and dark-gray sandstone.

Volcanic rocks constitute a small proportion of the formation. Some of these, which chemically and mineralogically are soda-rhyolites, are white to buff tuffs, breccias, and volcanic conglomerate. The well-rounded pebbles in the conglomerate average 4 inches in diameter, but attain a maximum size of 21 inches. The dark volcanics are described on the explanation accompanying the geological map as chlorite schist and chlorite-actinolite schist. Although some are schistose, others are relatively massive. Some even retain an ophitic texture. They were originally andesites and basalts. The volcanic member, including some interbedded black slate, is from 700 to 800 feet thick. But 6 miles west of Littleton this zone pinches out and is absent to the north.

An unusual occurrence of the Littleton formation lies 3 miles north-northeast of North Conway in the east-central part of the state (Billings, 1928, p. 80). These rocks, in the chlorite zone, cover an area 1,800 feet long and not over 400 feet wide. Although chiefly dark-gray slate, there are some thin beds of quartzite. On lithologic grounds these rocks have been correlated with the Littleton formation. In adjacent areas the Littleton is in the sillimanite zone. These anomalous, low-grade rocks are believed to have been dropped down from a higher level by cauldron subsidence, as described on a later page.

Rocks of the Littleton formation in the biotite zone are shown on the geological map in only two places. One is 6 miles east-southeast of Hanover, the other is 6 miles southwest of Claremont. A white quartzite and quartz conglomerate in this area, shown as a member of the Littleton formation, may actually belong to the Clough quartzite (Thompson, 1954). In these areas the Littleton formation consists of phyllites or fine-grained mica schists that carry some biotite. These rocks may actually belong in the garnet zone. The absence of the critical index mineral may be because of unfavorable chemical composition or inadequate field observations.

In the Littleton formation that extends southwest from the Gale River west of Franconia to the southern border of New Hampshire, much of the Littleton formation lies east of the garnet isograd, but west of the sillimanite isograd; that is, within this area, the Littleton formation is in the garnet and staurolite zones. The formation is composed chiefly of gray quartz-mica schist and gray mica schist. In many places the mica schists contain porphyroblasts of biotite and garnet. The garnets, characteristically euhedral, showing dodecahedrons and trapezohedrons, are generally from 0.5 to 2 mm. in diameter; they are probably almandite. Porphyroblasts of staurolite, as well as biotite and garnet, are typically present in the staurolite zone. In some places the staurolite is euhedral, bounded by the unit prism and the side pinacoid; elsewhere it is irregular. Staurolite crystals 1 cm. long are not uncommon and locally they attain a length of 4 to 5 cm. and even 10 cm. (Billings, 1937, p. 491; Kruger, 1946, p. 174; Moore, 1949, p. 1629).

Although mica schist and quartz-mica schist are the dominant rocks in the garnet and staurolite zones, other rocks are present. Metamorphosed volcanic rocks have been described from several localities. Two belts of volcanic rocks have been mapped in the band south of Barrett. The lower volcanic band, which lies near the base of the Littleton formation, is especially well exposed along the Gale River ¼ mile above its junction with the Ammonoosuc River. The volcanics, about 950 feet thick, consist of soda-rhyolite volcanic conglomerate, fine-grained biotite gneiss, amphibolite (some with pillow structure), and amphibolitic volcanic conglomerate. The fine-grained biotite gneiss, like that in the Ammonoosuc volcanics, is metamorphosed soda-rhyolite tuff and breccia. The amphibolites are metamorphosed basalts. The upper volcanic member, exposed near Northey Hill west-northwest of Franconia, is amphibolite tuff and breccia; it is probably only a few hundred feet thick.

Small bodies of volcanic rocks have been mapped within the Littleton formation in an area 15 miles long, north and south of Acworth (Kruger, 1946, p. 175). These are mostly amphibolites, but some garnetiferous fine-grained biotite gneisses are present. In the extreme southwestern corner of the state, because of the scale of the map, only one of several volcanic bands mapped by Moore (1949) are shown. They are interbedded amphibolites and fine-grained biotite gneisses.

Lime-silicate rocks have been described from south of Alstead. An unusually large area is shown 3 miles east of Walpole. Two other bands are shown west and northwest of Chesterfield. These rocks are green-gray actinolite granulite, green-gray actinolite-diopside granulite, purplish-brown biotite schist, and rusty-brown quartzite; the weathering of small amounts of calcite results in solution pits ⅛ to ½ inch deep. These rocks are as much as 125 feet thick east of Walpole (Kruger, 1946, p. 179). West of Chesterfield they attain a thickness of 1,200 feet (Moore, 1949).

Beds of white quartzite and white quartz conglomerate are also present from Claremont to the Massachusetts border. They are indicated on the geological map by a line that consists of an alternating dash and two dots. The pebbles in the conglomerates have been deformed into ellipsoids from 2 inches to several feet long. The quartzites consist of 70% to 97% quartz; the other minerals are biotite, garnet, muscovite, feldspar, and clinozoisite. These beds attain a maximum thickness of several hundred feet.

Within the Merrimack synclinorium and adjacent areas the Littleton formation is in the sillimanite zone. As in the other zones, the rocks are chiefly metamorphosed clastic sediments that were originally shales and argillaceous sandstones. Metamorphosed clean quartz sandstone, quartz conglomerate, impure dolomite, and volcanic rocks are distinctly subordinate.

Gray mica schists are one of the most common rocks. Although some of them are schistose, others are relatively massive. In addition to quartz, muscovite, and biotite, these rocks may have one or more of the following minerals: garnet, sillimanite, andalusite, and staurolite. Because of variations in the percentages of these minerals, differences in grain size, complicated paragenetic sequences, and variations in the perfection of the schistosity, a considerable variety of rocks has developed. One rock is a simple mica schist composed of quartz, muscovite, biotite, and a little oligoclase. Such rocks may be relatively fine-grained, others are very coarse-grained, with the muscovite from 2 to 10 mm. in diameter. Small crystals of garnet (almandine), generally 1 to 2 mm. in diameter, are in the garnet-mica schist. Microscopic study may reveal small needles of sillimanite. But in some places the sillimanite is megascopically conspicuous; it may be 10 mm. long and, exceptionally, 50 mm. long. In many instances these sillimanite crystals have been partially replaced by muscovite. Andalusite crystals, from 10 to 80 mm. long, although locally fresh and unaltered, have commonly been transformed to sericite or muscovite. Staurolite, although not typical of these rocks, is locally present, either in small grains in a shell around the sillimanite, or as separate euhedral crystals 1 to 5 mm. long. Small euhedral crystals of black tourmaline are present in some places.

Mica-quartz schists are gray schistose rocks containing from 60% to 80% quartz. They are the metamorphosed equivalents of rocks that were originally more arenaceous than the rocks from which the mica schists were derived. Light-gray micaceous quartzites are locally conspicuous.

In some areas the mica schists, with or without garnet and sillimanite, are interbedded with mica-quartz schists and/or micaceous quartzites. The individual beds may be from ½ to 12 inches thick (Heald, 1950, p. 48) or as much as 10 to 20 feet thick

(Billings, 1941, p. 887; Fowler-Billings, 1949, p. 1262). Such interbedded strata are beautifully exposed on Mt. Monadnock and in the Presidential Range.

In many places the Littleton formation in the sillimanite zone consists of rocks that are more appropriately described as gneisses or, in many cases, granulites. Such rocks are separately shown on the geological map in many parts of the state. Some of these gneisses are banded rocks that consist of alternating layers an inch or two thick; dark bands are rich in biotite, with some plagioclase and quartz, whereas the light-colored bands are composed chiefly of plagioclase, quartz, muscovite, and some biotite. In other gneisses the light-colored constituents form pods or lenses 1 to 3 inches thick and 3 to 10 inches long. Some rocks are mottled, consisting of irregular patches a few inches across; the dark patches are richer in biotite. Still other rocks are homogeneous, coarse-grained, granular rocks composed of quartz, biotite, muscovite, and oligoclase. Chemical analyses show that all these gneisses and granulites were originally shales. Pyritiferous gneisses are wide-spread in some places. They weather to rusty-brown or jet-black surfaces (Heald, 1950). The principal minerals are quartz, biotite, and muscovite, with lesser amounts of sillimanite; pyrite ranges from 1% to 5%, graphite from a trace to 2%. These rocks are metamorphosed black shale (Heald, 1950). In the southwestern part of the state, around Marlow and Sullivan, massive gneisses contain orthoclase porphyroblasts as much as 5 cm. long set in a coarse-grained matrix of quartz, biotite, sillimanite, and a little oligoclase and cordierite. These gneisses formed from the muscovite-biotite gneisses when the temperature became so high that muscovite, no longer stable, broke down into orthoclase and sillimanite.

In some places the gneisses of the Littleton formation carry blocks that differ greatly in mineralogy from the gneisses. Some of the blocks, which are angular, range in length from a few inches to 10 feet; they consist largely of quartz with minor amounts of mica. They are apparently fragments of more brittle beds that pulled apart during the deformation of the gneiss. But other blocks are ellipsoids ranging from 6 inches to 3 feet in length; they consist of quartz, garnet, amphibole, diopside, sphene, and calcic plagioclase. Some of the ellipsoidal blocks are concentrically zoned. They are considered to be metamorphosed dolomitic concretions (Billings et al, 1946, p. 264).

Lime-silicate rocks, originally impure dolomites, have been mapped locally. These are so thin that they are shown on the geological map by a dotted line. One band is present around Monadnock Mountain in the southeast corner of the state (Fowler-Billings, 1949). These beds range in thickness from zero to 660 feet. A second band, northwest of Marlow, is associated with the beds of quartzite (*Dlq*) that can be followed for 2 miles. These beds are about 130 feet thick (Heald, 1950). A third band, found around the Presidential Range, is from zero to 200 feet thick, (Billings, 1941; Billings et al, 1946). These lime-silicate rocks, which carry actinolite and diopside, are similar to those in the staurolite zone. Associated "rusty-brown quartzites" consist of quartz, plagioclase, biotite, and about 5% to 10% pyrite.

A few beds of white quartzite and quartz conglomerate are locally present in the Littleton formation of the sillimanite zone: (1) 3 miles south of Richmond; (2) 2 miles north of Marlow; and (3) 6 miles southwest of Gorham where they are associated with the lime-silicate beds but are not separately shown on the map. The maximum thickness in the area southwest of Richmond is 50 feet (Moore, 1949, p. 1617).

Thickness. In the type area northwest of the Ammonoosuc River the Littleton formation is 4,600 feet thick (Billings, 1937, p. 493). In the Mt. Washington area the lower gneisses are 1,400± feet thick, whereas the upper well-bedded schists and micaceous quartzites are 4,000± feet thick; the total is thus 5,400 feet (Billings, 1941, p. 840; Billings et al, 1946). In the Mt. Monadnock region the thickness is 16,400 feet (Fowler-Billings, 1949, p. 1254). In the vicinity of Marlow, the thickness is probably at least 16,000 feet (Heald, 1950, p. 47). Only in a comparatively few places are younger stratigraphic units preserved above the Littleton formation. Moreover, a pronounced angular unconformity separates the Littleton from the younger strata. Consequently, the amount that is preserved at various places may differ considerably.

Correlation. The belt northwest of the Ammonoosuc River, consisting of three separate areas, can be readily correlated on the basis of lithology, stratigraphic position above the Fitch formation, and by paleontology. The band extending through Northey Hill, although more highly metamorphosed than in the type locality, was originally lithologically similar. Moreover, the volcanics in the lower part of the formation in both areas show many similarities in their stratigraphic relations. Finally, both belts are part of a stratigraphic sequence that can be recognized in both areas. The band that has its northeasterly terminus 2 miles west of Franconia and can be followed southwest to the southern border of the state, can be similarly correlated because of its inferred original lithologic similarity to the type Littleton and especially because of its position in a six-fold stratigraphic sequence.

The rocks in the vast area within the Merrimack synclinorium are correlated with the Littleton for the following reasons. The high-grade schists of Mt. Moosilauke were first correlated as Littleton because, prior to the metamorphism, they were lithologically similar to the rocks in the type locality. Secondly, they occurred above the Clough formation on the east flank of a major anticline (Bronson Hill anticline). It is true that a large body of plutonic rock, the Bethlehem gneiss of the Mt. Clough pluton (structure map with the geological map), intervened between the Clough quartzite and the Littleton. On the other hand, the discovery of a *Spirifer* in the Mt. Moosilauke belt (Billings and Cleaves, 1935) supported the conclusion that the Mt. Moosilauke region consists of metamorphosed Littleton. The Littleton formation in the Mt. Moosilauke area can be followed continuously, by a circuitous route it is true, into the vast area of schists in central New Hampshire. These, in turn, can be followed southeast to the Fitchburg pluton.

A second major piece of evidence comes from southwestern New Hampshire around Acworth and Marlow. Near Acworth there is an axis depression in the Bronson Hill anticline. Here the Littleton formation, which may be traced southward from an area 3 miles west of Franconia, can be followed across the nose of the anticline into the Merrimack synclinorium. Moreover, because the Mt. Clough pluton ends northwest of Marlow, it is again possible to trace the Littleton formation into central New Hampshire. Moreover, north of Acworth, a complete stratigraphic sequence is preserved, including the Ammonoosuc, Clough, Fitch, and Littleton formations.

A large area somewhat north of east-central New Hampshire has been correlated with the Littleton formation. This area is bounded on the southwest by a line passing through Fabyan, Crawford Notch, and Jackson, on the southeast by a line passing

through Jackson and North Chatham, and on the northwest by a line passing near Fabyan, Randolph, and Mt. Success. This area is completely isolated from the Littleton formation in central New Hampshire by plutonic rocks, mostly belonging to the White Mountain plutonic-volcanic series. Hence, the metamorphic rocks cannot be traced continuously back to the areas described in preceding paragraphs. The rocks in this area east of Fabyan are correlated with the Littleton formation for several reasons. Lithologically they are identical with the Littleton formation in the sillimanite zone to the southwest. Secondly, south of Randolph, on the northern flanks of the Presidential Range, these metasedimentary rocks overlie the Ammonoosuc volcanics. The absence of the Fitch formation at the contact is not unexpected because 3 miles west of Whitefield the Littleton rests directly on the pre-Silurian rocks.

The small area of the Littleton formation 3 miles north-northeast of North Conway is correlated entirely on the basis of lithologic similarity and stratigraphic position beneath the Moat volcanics.

The Littleton formation is Lower Devonian (Billings and Cleaves, 1934). The paleontological evidence is discussed more fully on a later page.

Mississippian (?)

General Statement

The Moat volcanics are the extrusive phase of the White Mountain plutonic-volcanic series. As will be shown in detail in a later section, this series is younger than the Lower Devonian Littleton formation and, assuming it to be the same age as the Quincy granite and related rocks in Massachusetts, it is pre-Pennsylvanian. Moreover, recent radioactive age determinations (Faul, 1954, p. 267) show that the White Mountain series is Mississippian, and hence there is considerable justification for removing the query from the age designation.

Moat Volcanics

Name. The Moat volcanics have been so designated because of the excellent exposures on Moat Mountain, 4 miles west of North Conway (Billings, 1928).

Distribution. Large areas of the Moat volcanics are present in the following localities: (1) Moat Mountain, 4 miles west of

North Conway; (2) Mt. Pequawket, 4 miles north-northeast of North Conway; and (3) the Ossipee Mountains in the east-central part of the state. Smaller areas are found: (4) in the southern part of the Belknap Mountains south of Lake Winnipesaukee; (5) on Mt. Hale, 4 miles south-southeast of the village of Twin Mountain; (6) on North Twin Mountain, 5 miles south-southeast of the village of Twin Mountain; and (7) 3 miles southeast of the summit of Mt. Lafayette; debris in the streams in this area suggest that the body is larger than shown on the geological map.

Lithology. The Moat volcanics are primarily rhyolites, but contain a high percentage of andesite and basalt. Trachyte is distinctly subordinate. The rocks include flows, tuffs, and breccias. They differ from all the previously described formations in that they are younger than the regional metamorphism.

The rhyolite flows are light-gray, blue-gray, and red porphyries with phenocrysts of quartz and feldspar. The quartz, which is smoky or occasionally milky white, is 1 to 3 mm. in diameter; many crystals, although partially corroded, are doubly terminated. The feldspar phenocrysts are locally white, pink, or light-green-gray and 1 to 3 mm. long; miscroscopic study shows that they are microperthite. The groundmass, which is dense to fine-grained, is composed mostly of quartz and feldspar. Dark minerals, which are not abundant, are biotite, hastingsite, fayalite, and, in a few instances, riebeckite and aegerine-augite. Flow-banding is not common in the rhyolites.

The andesites and basalts are mostly confined to the Ossipee Mountains, although some andesite has been found on Mt. Hale. The andesites and basalts are dark-green to black, dense to fine-grained rocks that are difficult to distinguish from one another in the field. The feldspar phenocrysts, which range in length from 2 to 10 mm., are sodic bytownite in the basalts, whereas they range from sodic labradorite to calcic oligoclase in the andesites. Red trachyte, exposed on South Moat Mountain, contains two generations of feldspar phenocrysts; some are 2.5 mm. long, whereas others are only 0.2 mm. long; the feldspars are an irregular mixture of albite and orthoclase. The groundmass, which is even finer-grained, consists of small parallel crystals of soda-orthoclase associated with hematite.

The breccias have been studied in detail on Moat Mountain

and Mt. Pequawket by Billings (1928), and in the Ossipee Mountains by Kingsley (1931). The fragments are angular to subangular blocks, generally from a fraction of an inch to a foot in diameter, but, locally, as much as 5 feet in diameter. The small clastic fragments are quartz and feldspar. On Mt. Pequawket the common fragments are slate, with lesser amounts of quartzite. These fragments were derived from the Littleton formation on the south flanks of the mountain. Some rhyolite fragments are also present. On Moat Mountain the clastic fragments are slate, quartzite, andalusite schist, quartz-mica schist, quartz-chlorite-muscovite schist, binary granite (similar to the Concord and Bickford granites) and Kinsman quartz monzonite. The matrix of the breccias, which rarely show bedding, is rhyolite tuff composed of quartz and microperthite. In the Ossipee Mountains the fragments are over a foot in diameter; the most common rock is binary granite, but pegmatite, basalt, and rhyolite are also present.

The rhyolitic tuffs are gray, black, and red. Gray feldpathic tuffs are composed chiefly of quartz and feldspar, either microperthite or orthoclase. Dense black, gray, and red tuffs are locally present. In the Ossipee Mountains much of what appears to be massive basalt or andesite proves, on careful study, to be basaltic or andesitic tuff (Kingsley, 1931, p. 148).

The interbedding of the flows, tuffs and breccias is especially well shown on South Moat Mountain. Whereas the tuffs are generally only a few feet thick, the breccias and flows are hundreds of feet thick. The interbedding of the volcanics is also well shown in the Ossipee Mountains on Little Mt. Whittier, 1½ miles southwest of West Ossipee.

Thickness. The Moat volcanics on Moat Mountain are at least 11,800 feet thick, on Mt. Pequawket 9,200 feet thick, and in the Ossipee Mountains 7,000 feet thick (Billings, 1928, p. 92; Kingsley, 1931, p. 150).

Correlation. The various areas of Moat volcanics are correlated for the following reasons: (1) lithologic similarity; (2) lack of regional metamorphism; (3) a similar chronological position in that they are younger than the Littleton formation and the New Hampshire plutonic series but older than any known plutonic phases of the White Mountain series.

Southeastern New Hampshire

General Statement

Most of the metasedimentary and metavolcanic rocks in a band 20 miles wide in southeastern New Hampshire have been classified on the map as "probably Ordovician and Silurian." The northwestern boundary of this belt passes near Brookline, Merrimack, Massabesic Lake, Nottingham, and East Barrington. North of a line passing near Hampton Falls, Brentwood and Fremont, these rocks have been assigned to four formations: Rye, Kittery, Eliot, and Berwick. South of this line, because of a lack of detailed work, only the designation "Merrimack group" has been used. The term "Merrimack group" is intended to include the Kittery, Eliot, and Berwick formations, but not the Rye formation.

In the extreme southeastern corner of New Hampshire a small area has been mapped as Newburyport quartz diorite, which is pre-Cambrian or early Paleozoic. The Newburyport will be described in that part of this bulletin dealing with the plutonic rocks.

Ordovician (?)

Rye Formation

Name. The term "Rye gneiss" was proposed by Wandke (1922, p. 143) for a group of rocks typically exposed in the township of Rye, New Hampshire. However, the lithologic designation "gneiss" does not seem appropriate, and hence the more general term "formation" is used. The Rye formation is essentially the same as the "Algonkian complex" of Katz (1917).

Distribution. The Rye formation is confined to an area 12 miles long that trends southwest from New Castle to Hampton Falls. This band, which has a maximum width of 4 miles at the north, tapers out toward the southwest because it is in the core of a plunging anticline.

Lithology. The description of the lithology of this formation is based largely on reconnaissance work by M. T. Heald and the author in August, 1951. The formation has been divided into two members, a lower metasedimentary member and an upper metavolcanic member. Because of the increase in the grade of metamorphism toward the coast, the metasedimentary member is

found in the garnet, staurolite and sillimanite zones. In the garnet zone the rock is a feldspathic mica schist containing small garnet porphyroblasts up to 2 mm. in diameter. Along the coast sillimanite crystals up to 2 cm. long are sparingly present.

The metavolcanic member is in the garnet zone. It contains medium-grained amphibolite, representing metamorphosed andesitic or basaltic rocks, and fine-grained biotite gneiss, representing metamorphosed soda-rhyolite. Some schists have also been included in this member.

Thickness. Because of folding and the reconnaissance nature of the study, the thickness of the lower metasedimentary member is uncertain. A tentative figure of 2,000 ± feet is assigned. The metavolcanic member is also tentatively assigned a thickness of 2,000 ± feet.

Correlation. Since this one band is the type locality, no problem in correlation is presented. The formation is tentatively assigned to the Ordovician.

Silurian (?)

Kittery Quartzite

Name. This formation was named for the fine exposures around Kittery, Maine directly across the Piscataqua River from Portsmouth (Katz, 1917, p. 168).

Distribution. Four areas of Kittery quartzite are shown on the geologic map. One belt, which is continuous with the type locality, extends south-southwest from Portsmouth for 13 miles to Hampton Falls. A second band extends for 16 miles south-southwest from 1½ miles east of Dover to south of Exeter. Two small bodies lie west of the Exeter diorite; one of these, 3 miles long, is in Dover and the other, nearly 2 miles long, is 2 miles southwest of Newmarket.

Future detailed studies may modify the distribution of the Kittery quartzite. The most easterly band is shown as pinching out southward. Certainly the quartzite typical of the Kittery become less abundant southward. This may be the result of a change in sedimentary facies, the quartzites passing laterally into the slates and calcareous slates that have been mapped as Eliot. On the other hand, as shown on the geological map, the Kittery may everywhere lie beneath the Eliot, but thin rapidly to the south. Changes in grade of metamorphism further complicate the problem; calcareous slates may be metamorphosed to actinolite or actinolite-diopside granulites, which, unless studied carefully, may be mistaken for quartzites.

Lithology. The Kittery formation consists of gray quartzite, gray argillaceous quartzite, and gray slate. In places these lithologic types alternate in beds that are a few inches to several feet thick. Elsewhere, large outcrops consist of only one lithologic type.

Thickness. Because the structure has not been worked out in detail, the thickness is hard to estimate. Katz (1917, p. 167) gave a value of 1,500 (?) feet.

Correlation. The four areas of Kittery shown on the geological map are correlated entirely on the basis of lithologic similarity. The age is tentatively considered to be Silurian.

Eliot Formation

Name. "Eliot slate" was proposed by Katz (1917, p. 169) for a somewhat metamorphosed, argillaceous, sedimentary rock exposed in the township of Eliot in Maine, directly north of Portsmouth. Although slate is an appropriate lithologic appellation in the type locality, it is not satisfactory for those areas where the formation is more metamorphosed. Hence this stratigraphic unit is called the Eliot formation.

Distribution. On the geologic map the Eliot formation encircles the elongate stock of Exeter diorite. East of the diorite, the Eliot forms a band 3 miles wide that lies between Portsmouth and Dover. This belt extends south-southwest to east of Exeter. Much of the northern part of this area is covered by the waters of Great Bay. The Eliot continues around the south end of the Exeter diorite. The band on the west side of the Exeter diorite can be traced from Brentwood to north of Dover; it is 20 miles long and from 1 to 4 miles wide. In the extreme southeastern corner of the state, one branch of this body of Eliot extends eastward from Hampton Falls to the coast. Southwest of Brentwood and Exeter, much of the rock that is shown on the map as Merrimack group belongs to the Eliot formation.

Lithology. Where least metamorphosed, the Eliot formation is composed largely of easily weathered slates, quartzose slates,

and calcareous slates. These rocks, gray on fresh surfaces, are buff colored in normal exposures. Freedman (1950, p. 455) says that quartzites constitute about 15% of the formation; they are green-gray to blue-gray rocks. Although some outcrops are composed of one kind of rock, others consist of several kinds in alternating beds a few inches to a few feet thick.

The Calef member is at the top of the Eliot formation. It occupies a band 6 miles long extending from Epping in the southwest to Lee on the northeast. It is named from the Calef Highway. which follows this member for some distance (Freedman, 1950, p. 456). It is chiefly a black phyllite, but also contains some green quartz-chlorite phyllite (Freedman, 1950, p. 456 and Plate 1). The maximum thickness of this member is 800 feet.

With an increase in the grade of metamorphism, the Eliot passes into the biotite zone. Here, because of the appearance of biotite, the rocks, where fresh, take on a purplish-brown hue. The rocks are best described as purplish-brown biotite schist. More quartzose rocks become quartz-mica schist. Calcareous rocks become brown biotite-actinolite schist and green-gray actinolite granulite.

Thickness. Freedman (1950, p. 453) gives the thickness of the Eliot formation as 6,500 feet.

Correlation. The area mapped as Eliot is directly continuous with the type locality. The age is tentatively considered to be Silurian, probably Middle Silurian.

Berwick Formation

Name. Katz (1917, p. 166-167) proposed the name "Berwick gneiss" for this formation. The locality name comes from the town of Berwick in Maine, directly across the Salmon Falls River from Somersworth. Freedman (1950, p. 456) proposed that this unit be designated "formation" rather than "gneiss."

Distribution. There is only one band of the Berwick formation. Twenty-four miles long and 3 to 6 miles wide, it extends south-southwest from Somersworth to southwest of Raymond. Further southwest it is mapped as part of the Merrimack group.

Lithology. Much of the difference between the Eliot and Berwick formations is the result of a difference in the grade of metamorphism. Whereas the Eliot is mostly in the chlorite zone and, locally, in the biotite zone, the Berwick formation lies chiefly in the garnet, staurolite, and sillimanite zones, although in a few places is in the biotite and chlorite zones. In the chlorite and biotite zones the lithology is much like that of the Eliot formation. In the garnet, staurolite, and sillimanite zones it is chiefly purplish-brown biotite schist and gray quartz-mica schist; less common rocks are green-gray actinolite granulite and brown biotite-actinolite granulite. Although many large outcrops consist of one kind of rock, in others the various types are interbedded in beds from 6 inches to 3 feet thick.

The Gove member, a band 6 miles long and 700 feet wide, is silvery mica-schist, some of it containing staurolite and sillimanite. The name comes from Gove School, 2 miles northeast of Raymond (Freedman, 1950, p. 460). The maximum thickness is 200 feet.

Katz (1917) separated the Berwick formation from the Eliot formation because of their differences in lithology. He erroneously assumed that this meant a difference in age. The descriptions by Freedman (1950) indicate that the two formations must have been very similar prior to metamorphism. Nevertheless, structural studies indicate that the rocks mapped as Berwick are stratigraphically above those mapped as Eliot. The Calef member lies between the two stratigraphic units and has been arbitrarily assigned to the Eliot formation.

Thickness. Freedman (1950, p. 455) gives the thickness of the Berwick formation as 7,000 feet but, as discussed below, some of the rocks that Freedman assigned to the Littleton formation are here considered to be part of the Berwick. The total thickness of the formation is hence probably 10,000 feet.

Correlation. All the rocks mapped as Berwick are continuous with those in the type locality. On the accompanying geological map the rocks northwest of the Gove member and southeast of the Fitchburg pluton (*gqg* on the geological map) are assigned to the Berwick. Freedman (1950) assigned these rocks, as well as the Gove member, to the Littleton formation. But Billings and Heald in 1951 showed that, in general, these rocks are similar with those in the Berwick; purplish-brown biotite schists are especially abundant, whereas the aluminous minerals characteristic of the Littleton formation such as muscovite, sillimanite, and andalusite are absent.

The Berwick is tentatively considered to be Silurian, perhaps Middle Silurian.

Merrimack Group

Name. "Merrimack group" was apparently first used in a publication by C. H. Hitchcock in 1870 (Wilmarth, 1938, p. 1353). The type locality was along the valley of the Merrimack River in Massachusetts. The distribution of the Merrimack group is shown on the Geological Atlas accompanying Hitchcock's report (1878). In the present publication the Merrimack group is used in much the same sense as by Hitchcock, except that the Rye formation is here excluded. Moreover, that part of Hitchcock's Rockingham mica schist lying southeast of the Fitchburg pluton is included in the Merrimack group.

Distribution. The Merrimack group occupies all of extreme southeastern New Hampshire south of a line passing through Hampton Falls, Brentwood, and Fremont, and southeast of a line passing near Brookline, Merrimack and Massabesic Lake, except for areas of plutonic rocks.

Lithology. Most of the rocks are similar to those in the Eliot and Berwick formations. In the chlorite zone they are buff slate, buff quartzose slate, and gray calcareous slate. In the higher metamorphic zones they are chiefly purplish-brown biotite schist and gray quartz-mica schist; less common are green-gray actinolite granulite and brown biotite-actinolite schist. Local phyllite and mica schist bands are shown on the map. One of these, 6 miles long and ½ mile wide, trends northeast in the vicinity of Newton; it is a dark-gray phyllite. A second band, one mile west of Hollis, extends 3 miles north from the Massachusetts border; it is likewise a dark-gray phyllite. A third, discontinuous band, 26 miles long, lies southeast of the Fitchburg pluton (*gqg* on the geological map) from Massabesic Lake to the Massachusetts border. This is a gray, coarse-grained mica schist with sillimanite.

Thickness. Since the Merrimack group is the equivalent of the Eliot and Berwick formation, the thickness would be about 16,500 feet. Mr. Aluru Sriramadas says that the part of the Merrimack group exposed in the Manchester quadrangle along Route 28 between Canobie Lake and Massabesic Lake is 16,000 feet thick.

Correlation. In accordance with the original nomenclature of Hitchcock, this region is the type locality of the Merrimack group. The term "Merrimack group," as used in this paper, is much more inclusive than the "Merrimack quartzite" of Massachusetts (Emerson, 1917). The Merrimack group includes the following formations shown on Emerson's map: (1) Merrimack quartzite, (2) Oakdale quartzite (which Emerson considered to be the stratigraphic equivalent of the Merrimack quartzite), and (3) gneisses of unknown age and origin. Moreover, Emerson mapped the band of phyllite near Hollis as Worcester phyllite; he mapped the mica schist directly southeast of the Fitchburg pluton as Brimfield schist. Emerson considered the Worcester and Brimfield to be stratigraphic equivalents.

Although some geologists have considered the Merrimack quartzite of Emerson to be wholly or partly the equivalent of the Kittery quartzite, it appears from the geologic map of New Hampshire that the Merrimack quartzite of Massachusetts is the equivalent of the Eliot formation. It should be pointed out that the Merrimack quartzite of Massachusetts is at best an impure quartzite because it contains actinolite and biotite (Emerson, 1917, p. 58). Equivalents of the Kittery formation may be exposed in Massachusetts in the cores of doubly plunging anticlines.

On the geological map of New Hampshire the Merrimack group has been tentatively assigned to the Silurian.

PLUTONIC ROCKS

General Statement

On the accompanying geologic map the plutonic rocks have been classified into seven series. One, relatively unimportant in New Hampshire, is the Newburyport quartz diorite, which has been dated as pre-Cambrian or Early Paleozoic. A second, confined to one area in northernmost New Hampshire, is serpentine—probably Late Ordovician. The third is the Ordovician (?) Highlandcroft plutonic series, confined to the western part of the state. A fourth, which is extensively developed in a band 2 to 12 miles wide that extends from the southwest corner of the state to the Maine border northeast of Berlin, is the Oliverian plutonic series; on the map it is dated as Middle or Upper Devonian (?). A fifth, the Upper Devonian (?) New Hampshire plutonic series, is widespread as large bodies throughout the state. A sixth group, in the southeastern part of the state will be referred to in the text as the Hillsboro plutonic series, although it is not so designated on the geological map; it may belong to the New Hampshire series. A seventh, the Mississippian (?) White Mountain plutonic-volcanic series, occupies a broad band trending north-south across the older structural framework of the state.

Pre-Cambrian or Early Paleozoic

Newburyport Quartz Diorite

Name. The Newburyport quartz diorite is named from the City of Newburyport in eastern Massachusetts, 4 miles south of Seabrook, New Hampshire.

Distribution. The Newburyport quartz diorite occupies a small area in the extreme southeast corner of the state east of Seabrook.

Lithology. The description of the lithology is based on field observations made by Billings and Heald in 1951 and on a study of thin sections made by Billings. In New Hampshire, the southern part of the area mapped as Newburyport consists of a relatively uniform medium-grained to coarse-grained, dark-colored quartz diorite consisting principally of quartz, saussuritized andesine, hornblende, and chlorite. Microscopic study shows that the chlorite has been derived from biotite. The andesine has been almost completely converted to sericite, with a little epidote. The hornblende appears to be secondary. Small amounts of sphene, microcline, and pyrite are present.

A band about ½ mile wide in the northernmost part of the area mapped as Newburyport quartz diorite is much more heterogeneous. It is especially well exposed on the ledges at Beckmans Point, 3 miles east of Seabrook. The rock here is a streaked plutonic breccia composed of (1) fine-grained quartz diorite, (2) medium-grained hornblende-chlorite diorite, (3) medium-coarse hornblende-chlorite diorite, and (4) medium-grained, light-colored biotite-quartz diorite. The fine-grained quartz diorite occurs as angular blocks a few inches to 2 feet long in the second and third types. The fourth variety occurs as streaks and dikes a few inches wide cutting all the other types. The first three types are probably brecciated Newburyport, whereas the fourth type is probably related to much younger granites shown to the west on the map.

Correlation. The area mapped as Newburyport is continuous with the exposures in the type locality. In Massachusetts the Newburyport is considered to be one member of a consanguineous series called the "Dedham granodiorite and associated rocks" (Emerson, 1917, p. 172-181). Billings (1929) and Dowse (1950) have shown that the Dedham is pre-Cambrian; hence it follows that the entire series is pre-Cambrian. However, LaForge assigned this group to the Early Paleozoic (LaForge, 1932, p. 21-28), and he has stated (personal communication) that he thought it might be contemporaneous with the Taconic disturbance.

Ordovician (?)

Serpentine

Only one body of serpentine is shown on the geological map; it is in the extreme northeast corner of the state. It is shown on Hitchcock's map (Hitchcock, 1878) but no further information seems available.

Highlandcroft Plutonic Series

Name. This series was named from Highlandcroft Farm on the western outskirts of the village of Littleton (Billings, 1935, p. 25). The type area is the body of plutonic rocks 2 miles northwest of Littleton.

Distribution. The Highlandcroft plutonic series occurs in isolated bodies in the extreme western part of the state in an area 50 miles long, extending from near Orford on the southwest to north of Lancaster on the north. All these bodies lie northwest of the Ammonoosuc thrust. Two small patches, shown southwest and northwest of Piermont, are actually parts of one body that is more extensively developed in eastern Vermont. A second area is the type locality northwest of Littleton. A third area, 2 miles southwest of Littleton, is a small slice along the Ammonoosuc thrust. A fourth area, 6 miles west-northwest of Littleton, is part of a larger body in eastern Vermont. The fifth and largest area is around Lancaster; in New Hampshire it is 12 miles long and has a maximum width of 8 miles.

Lithology. This series shows a considerable range in composition, including diorite, quartz diorite, granodiorite, quartz monzonite and granite. The various lithologic types have not been distinguished on the geologic map. Many of the rocks are massive, but locally show a weak to strong secondary foliation. The dark minerals are hornblende and biotite; pyroxene and muscovite, common in some of the other series, are absent. Approximate modes are given in Table 6.

In the type locality the rock is a green-gray, medium-grained granodiorite in which the grains are 2 to 3 mm. in diameter. The chief minerals are green-gray saussuritized plagioclase, white to pink microcline, milky quartz, hornblende, and "green biotite." The rock near Piermont, which has been called the Fairlee quartz monzonite (Hadley, 1942, p. 136), is a coarse-grained, green-gray to pink granitoid rock that is locally sub-porphyritic. Weakly to strongly schistose, the principal minerals are blue-gray quartz, perthitic microcline, saussuritized plagioclase, biotite, and some chlorite and sericite. A similar rock is found 2 miles northwest of Littleton in the slice along the Ammonoosuc thrust.

The rocks in the large area around Lancaster are chiefly quartz diorite, with lesser amounts of diorite. Only the rocks in the extreme eastern part of the area have been described in detail, where they have been called the Lost Nation group (R. W. Chapman, 1948, p. 1072-1074). The quartz diorite is massive, dark-gray, has an average grain size of 1 to 2 mm., and is composed of plagioclase (andesine), quartz, biotite, hornblende, and epidote. The diorite, which is massive, dark-gray and somewhat coarser than the quartz diorite, has a grain size of 2 to 3 mm.; the principal minerals are plagioclase (andesine), hornblende, some biotite, and a little or no quartz.

Correlation. The rocks assigned to the Highlandcroft series are correlated chiefly on the basis of lithologic similarity. Although there are considerable differences in both the mineralogy and the grain size, there are certain features characteristic of the whole series. These include mineralogy and the generally massive to weakly schistose character. Moreover, these rocks are similar in being younger than the adjacent Ordovician (?) rocks.

Lahee (1913) showed that the Highlandcroft plutonic series (he called it the "Fitch Hill granite gneiss" in the area west of Littleton) is younger than the Ammonoosuc volcanics (Lahee's "Lyman schists") but older than the Fitch formation (Lahee's "Niagaran"). Hence, on stratigraphic evidence the Highlandcroft is pre-Silurian, probably Late Ordovician. Recent radioactive age determinations by J. B. Lyons demonstrate that the Highlandcroft is 385 million years old, indicating an Ordovician age. Table 6 shows that much of the Highlandcroft series has been metamorphosed in the chlorite zone; this took place during the Acadian revolution.

Middle or Upper Devonian (?)

Oliverian Plutonic Series

Name

This series was named from Oliverian Brook, a small stream that flows west-northwest through East Haverhill and Pike to join the Connecticut River near Haverhill. The valley of Oliverian Brook crosses the Owls Head granite, one of the units in the Oliverian plutonic series.

Distribution

This series is conspicuous in a belt 2 to 12 miles wide that extends from the southwest corner of the state to the Maine border northeast of Berlin. The anticline that contains most of the bodies of the Oliverian plutonic series has been called the Bronson Hill anticline (structure map accompanying the geological map). Within this anticline are numerous domes, the cores of which are occupied by rocks belonging to the Oliverian series.

Many of these domes, because of their structural importance, have been given locality names. The Oliverian plutonic series is especially abundant in the following places: (1) In the southwest corner of the state, where these rocks form the cores of the Vernon and Westmoreland-Swanzey-Surry domes; (2) in the core of the Mascoma dome, 8 miles east of Lebanon; and (3) in the large Jefferson dome, which extends for 40 miles from Franconia to northeast of Berlin. The Lebanon granite, primarily because of its lithology and structure, has been assigned to the Oliverian plutonic series.

General Description

The Oliverian plutonic series has certain general characteristics that distinguish it from the other series in the state. Many of the rocks are pink, foliation and/or lineation are common, and a granoblastic texture is characteristic. The deformation that this series has undergone distinguishes it from the White Mountain plutonic-volcanic series, whereas the pink color and more extreme granulation distinguishes it from the most characteristic units of the New Hampshire plutonic series. Biotite is the principal dark mineral, although hornblende is present in some of the more mafic phases. Octahedra of magnetite and grains of epidote are also distinctive of this series. The great bulk of the rocks assigned to the Oliverian series are shown on the geological map under the color-pattern for granite, quartz monzonite, and granodiorite (*ol*). The other units assigned to the Oliverian are far less extensive. Approximate estimated modes for some members of this series are given in Table 7.

Amphibolite

The amphibolite 1½ miles west of Lebanon is tentatively assigned to the Oliverian series. It is a medium-grained, black rock composed of hornblende and plagioclase (Lyons, 1955).

Whitefield Gneiss

This unit lies in a belt 22 miles long and 2 miles wide extending from Barrett on the southwest to Riverton on the northeast. Six miles southwest of Whitefield the body of Whitefield gneiss is interrupted by the granite of Hedgehog Hill. The locality name comes from the town of Whitefield, in which the rock is well exposed. The Whitefield gneiss is a dark-gray, medium-grained, foliated biotite granodiorite gneiss. It is very similar to the Bethlehem gneiss. In fact, the southwest end of this body was the type locality for the Bethlehem gneiss as redefined by Billings (1937, p. 504). But 4 miles south of Lancaster, dikes of pink quartz monzonite of the Oliverian intrude the Whitefield gneiss, indicating that the Whitefield cannot be part of the New Hampshire plutonic series.

Granite, Quartz Monzonite, and Granodiorite

The rocks described under this designation comprise most of the Oliverian plutonic series. They are generally pink to gray, medium-grained to coarse-grained rocks that are characteristically, but not necessarily, foliated and/or lineated; a granoblastic texture is typical. The principal dark mineral is biotite, which constitutes only a few percent of the rock. Small euhedral crystals of magnetite, averaging 1/8 inch across, are typical but not abundant. Depending upon the ratio of the two feldspars, the rocks may be classified as granite, quartz monzonite, granodiorite, and, rarely, quartz diorite. Although most of the published maps show these various types (Moore, 1949; Hadley, 1942; C. A. Chapman, 1939; Page, 1942, Billings, 1937; Billings et al, 1946), the boundaries cannot be located precisely because the various types are transitional into one another. Numerous locality names have been used for the different units, but to repeat them here is unnecessary.

Hornblende-quartz monzonite

These rocks have been separately indicated on the geological map in two localities, one in the west-central part of the state 4 miles west of Warren, a second southeast of Jefferson. West of Warren the rock is a well-foliated, dark-green-gray quartz monzonite that is locally a quartz diorite. The principal minerals are saussuritized andesine, hornblende, biotite, potash feldspar and quartz. In the vicinity of Jefferson the hornblende-quartz monzonite is a very heterogeneous rock. Medium-grained to coarse-grained, in some places it is porphyritic, elsewhere it is non-porphyritic. In the porphyritic rocks, pink to white crystals of microline, showing Carlsbad twinning, are set in a dark-gray groundmass of oligoclase or andesine, microcline, quartz, hornblende, and biotite. The non-porphyritic type is identical with the groundmass of the porphyritic type.

Syenite

Syenite occupies a large area between Jefferson and the Upper Ammonoosuc River 6 miles west of Berlin. This body of syenite, except for interruptions by the younger White Mountain plutonic-volcanic series, is 12 miles long and 7 miles wide. The rock is a coarse-grained to medium-grained pink syenite that is generally foliated. The most important mineral is pink microcline, in crystals that are 1/4 to 1/2 inch long, showing Carlsbad twinning. The other minerals, which are much smaller than the microcline, are oligoclase and lesser amounts of hornblende, biotite, and magnetite.

Lebanon Granite

Although the Lebanon granite has been assigned to the Oliverian plutonic series on the geological map, it occupies a different structural position than all the other members of this series. The others lie within the Bronson Hill anticline, whereas the Lebanon granite lies 8 miles west of the center of the anticline. The locality name, taken from the city of Lebanon, was first used by C. H. Hitchcock (1908). The Lebanon granite (C. A. Chapman, 1939, p. 146; Kaiser, 1938; Lyons, 1955, p. 118) is a medium-grained to coarse-grained biotite granite that is somewhat granulated. Microcline, which is the most abundant mineral, occurs as broken, partly granulated phenocrysts, generally less than 1 cm. long, or as smaller grains 0.2 to 0.3 mm. in diameter. A small amount of sodic oligoclase is present. Quartz constitutes about 1/3 of the rock. Small amounts of biotite, muscovite and epidote are present.

A band, from 1,000 feet to 1½ miles wide, surrounding the Lebanon granite has for many years been designated the border gneiss (Merritt, 1913). It is a heterogeneous, dark-gray, fine-grained to medium-grained granulated gneiss that is generally foliated, but locally shows only lineation (C. A. Chapman, 1939, p. 145). The composition is variable. The most mafic rocks are amphibolite, composed chiefly of hornblende and andesine, but with significant amounts of epidote, biotite, quartz, and a little microcline; these rocks were probably originally gabbro. The quartz diorites are composed chiefly of oligoclase and quartz, with a significant amount of biotite and a little epidote. Granodiorites are similar but have some potash feldspar. The quartz monzonites are composed of quartz, microcline, oligoclase, with some muscovite, biotite, epidote and calcite.

Pegmatites

Pink pegmatites are associated with the Oliverian series. Composed of pink potash feldspar, white oligoclase, quartz, biotite, and muscovite, they range in size from small dikes and sills to bodies that are many hundreds of feet long and many tens of feet thick. They have been described so adequately in previous publications that special description seems unnecessary here (Olson, 1942, 1950; Cameron et al, 1945; Cameron et al, 1954, especially pp. 15-19).

Correlation

In the main band of the Oliverian series, extending from Massachusetts to the Maine border, the correlation is based on the following. The rocks are lithologically similar: (a) they are generally pink; (b) many are foliated; (c) a granoblastic texture is characteristic; and (d) although the percentages of the minerals may differ, the mineralogy is similar, including such distinctive minerals as magnetite and epidote. The correlation is also based on the structural position of the intrusives: (a) most of them occur in the core of domes; (b) the top of the Oliverian series is in the upper part of the Ammonoosuc volcanics; and (c) the intrusives are older than or contemporaneous with the deformation. The Lebanon granite is correlated with the Oliverian series on the basis of (a) its pink color, (b) the granulation, (c) the fact that it is in a dome, and (d) the fact that it is contemporaneous with or older than the deformation.

Relative Ages

On the geological map, the Oliverian plutonic series has been divided into six major map units, but the order in the explanation has no great significance. The Whitefield gneiss, however, is older than the rocks classified as granite, quartz monzonite, and granodiorite (*ol*). Small dikes of these pink rocks cut the Whitefield north of Franconia and 4 miles northeast of Whitefield. Similarly, intrusive amphibolites in several places are cut by the pink granitic rocks of the Oliverian series. However, there is no evidence bearing on the relative age of the four topmost units of the Oliverian shown in the explanation.

Age

The Oliverian plutonic series has been assigned to the Middle or Upper Devonian (?) on the geological map. The rocks of the Oliverian are younger than the Ammonoosuc volcanics because sills of the former intrude the latter (Billings, 1937, p. 502; Hadley, 1942, p. 141; Billings, 1941, p. 896). Moreover, as shown on the geological map, the Oliverian plutonic series is in contact with the Clough quartzite 4 miles north of Mascoma Lake. The Clough has been feldspathized by solutions emanating from the Oliverian (Billings, 1937, p. 502). The age is discussed more fully on a later page.

Upper Devonian (?)

New Hampshire Plutonic Series

Name

This series received its name because of its extensive development in New Hampshire (Billings, 1934).

Distribution

As shown on the map, the New Hampshire plutonic series is widespread through the central and southwestern parts of the state. Moreover, the plutonic rocks in the southeastern part of the state (Hillsboro plutonic series), although separately designated on the geological map, probably belong to this series. Only in northern Coös County is the New Hampshire plutonic series rare. These rocks are contemporaneous with the Acadian orogeny, when the major folding took place in New Hampshire.

General Description

The New Hampshire plutonic series has certain general characterisistics that distinguish it from the other plutonic series in the state. Biotite is the principal dark mineral in the most important units. Muscovite, which is present in most members of this series, distinguishes it from the younger White Mountain plutonic-volcanic series. The rocks of the New Hampshire series are generally, but not universally, gray, whereas the rocks of the Oliverian series are generally pink. In general, granulation is more intense in the Oliverian than in the New Hampshire series. Pegmatites associated with the Oliverian series are believed to be pink, whereas those associated with the New Hampshire series are believed to be white; pegmatites associated with the White Mountain series are rare and have a distinctive mineralogy. Some approximate average modes of the New Hampshire plutonic series are given in Table 8.

Diorite

Name and Distribution. Diorite belonging to the New Hampshire series is very restricted in its development and hence is confined to a few small bodies. Only one of these is shown on the geological map, 6 miles west-southwest of Littleton. It has been called the Moulton diorite, from Moulton Hill, 2½ miles west-southwest of Lisbon (Billings, 1937), where a body of diorite, too small to show on the geological map accompanying this report, is exposed. The body shown on the map actually consists of two separate intrusions, each ½ mile long, but because of the scale, they are shown as one. Several other small bodies of diorite in this area are not shown on the map.

Lithology. The diorite is a medium-grained, dark-gray metadiorite, consisting chiefly of such secondary minerals as oligoclase, hornblende, epidote, chlorite, and calcite. This mineral assemblage indicates that the rock was originally diorite, but has undergone low-grade metamorphism.

Age. Inasmuch as some of the bodies of the diorite cut the Littleton formation (Billings, 1937, p. 502), it is younger than the Lower Devonian and is considered to be an early member of the New Hampshire plutonic series.

Quartz Diorite

Names. The quartz diorites are shown by only one color-pattern on the geological map, but in the various quadrangle reports different names have been used. In the central part of the state they have been called Winnipecaukee quartz diorite (Smith, Kingsley and Quinn, 1939; Quinn, 1944; Quinn, 1953). Hitchcock called these rocks "Winnipiseogee gneiss" (Hitchcock, 1877, p. 595-599) because they are so extensively developed around Lake Winnipesaukee. In the Monadnock quadrangle these rocks were called Spaulding quartz diorite, from Spaulding Hill, 3 miles east of Marlboro (Fowler-Billings, 1949). Similar rocks north of Littleton and 1 mile west of Lisbon were called Remick tonalite, the locality name being chosen from Remick Park, a municipal park in Littleton (Billings, 1937, p. 517).

Distribution. The Winnipesaukee quartz diorite forms a large irregular body covering many square miles around Lake Winnipesaukee. Several small bodies crop out on the flanks of the Ossipee Mountains, as well as east and west of the village of Whiteface. In the southwestern part of the state eleven bodies of quartz diorite are shown northwest, south, and east of Mt. Monadnock; on the geological quadrangle map they have been called Spaulding quartz diorite. The largest of these bodies is 4 miles long and 2 miles wide. Two bodies of Remick tonalite lie 1 mile north and 10 miles southwest of Littleton. Another body of quartz diorite is 5 miles south-southwest of Lebanon. Three small bodies are shown on the map 1, 2, and 4 miles, respectively, northwest of Wilton. West of Rochester three bodies of quartz diorite have been mapped. Quartz diorites are also present both north and south of the Androscoggin River around Shelburne, but they are too small to show on the scale of the geological map.

Lithology. The quartz diorites are dark-gray to light-gray, medium-grained rocks that are massive to well foliated. The principal dark mineral is biotite, although locally there is some hornblende. The light-colored minerals, which are distinctly dominant, are quartz and sodic plagioclase, either andesine or oligoclase.

Around Lake Winnipesaukee (Quinn, 1944, p. 478) the grain size is commonly 2 to 4 mm., although phenocrysts may be as much as 10 mm. in diameter. Quartz diorite is by far the most abundant type, but where orthoclase is present, the rock is granodiorite, quartz monzonite, or even granite. Locally quartz is so unimportant that the rock is diorite. In the Mt. Monadnock region the rock is chiefly quartz diorite, although occasional specimens are granodiorite. The plagioclase is oligoclase-andesine. A mottled effect is given to the rock because of a somewhat uneven distribution of the biotite. In the area southwest of Rochester, where the plagioclase is also oligoclase-andesine, hornblende averages about 4% of the rock, whereas biotite is 13%.

Bethlehem Gneiss

Name. The name Bethlehem gneiss was proposed by Hitchcock (1877, Vol. 2, p. 104) from exposures within the town of Bethlehem. It is now clear that by Bethlehem gneiss Hitchcock meant the rocks now classified as the Oliverian plutonic series. To describe all the misadventures that further confused the nomenclature would merely bore and confound the reader. In the strictest sense the term Bethlehem gneiss should be abandoned and a new name used in its place, but the present usage is so well-rooted in New Hampshire geological literature for the last two decades that this also seems inadvisable. The type locality for the Bethlehem gneiss, as the term is now used, may be considered to be the exposures on Green Mountain, which lies 2 miles southwest of Landaff.

Distribution. The largest body of Bethelehem gneiss, which forms the Mt. Clough pluton (structure map), has its northern terminus 2 miles southeast of Franconia. From here it may be followed for 76 miles south-southwest to 3 miles northwest of Marlow. Although less than a mile wide in places, elsewhere this body reaches a maximum width of 8 miles.

Several additional bodies lies west of the main mass. One body, 10 miles long and nearly 2 miles wide, extends from west of Landaff to north of Pike. Another body, 14 miles long and nearly 2 miles wide, extends from 3 miles east of Piermont to 3 miles southeast of Lyme. A fourth irregular body lies between Alstead and the Connecticut River. Evidence will be offered in the section on structural geology that the main mass of the Bethlehem gneiss and the bodies lying west of it all belong to a single intrusion.

Lithology. The Bethlehem gneiss is a dark-gray to light-gray, medium-grained biotite gneiss, strongly to weakly foliated, but locally unfoliated. The first impression is that the grains are 3 to 5 mm. in diameter, but closer scrutiny shows that many of these grains are actually aggregates of much smaller, sub-rounded grains 0.1 to 0.5 mm. in diameter; the texture is thus granoblastic because of post-consolidation deformation. The principal minerals are quartz, oligoclase-andesine, biotite, potash feldspar, and a small amount of muscovite. White phenocrysts of microcline, from 3 to 20 mm. long, locally constitute several percent of the rock and, in a few places, make up 10% of the rock. In general, the plagioclase is more than twice as abundant as potash feldspar; the rock is thus a granodiorite, although close to a quartz monzonite. Hadley (1942, p. 142) concluded that much of the body between Orfordville and Mt. Cube was quartz monzonite, but some was granodiorite, and a small percentage was granite. In that part of the main body between Canaan and Grantham the

Bethlehem is said to range from granodiorite to granite, but most of the published modes are granodiorite (C. A. Chapman, 1939); some of the phenocrysts of microcline are as much as 10 cm. long. Around Newport (C. A. Chapman, 1952) the Bethlehem ranges from quartz diorite to quartz monzonite, but the average is granodiorite; the microcline phenocrysts are commonly 5 cm. and even 7 cm. long. In the southern end of the body around South Acworth, the Bethlehem is mostly granodiorite with a little quartz monzonite (Heald, 1950).

Foliation is characteristic of the Bethlehem, but it differs in intensity, so that in some places the rock is very schistose, whereas elsewhere it is very massive. In many places biotite shows a lineation that may or may not be accompanied by foliation.

Slab-like inclusions are widespread but not abundant (Billings, 1937, p. 504; C. A. Chapman, 1952, p. 394; Heald, 1950, p. 56). They are parallel to the foliation, 1 to 5 inches wide, and are composed of mica schist. Near the south end of the main body a large inclusion, 1¼ miles long and up to ½ mile wide, is shown on the geological map. Heald (1952, p. 56) describes finer-grained bands, a few inches to several feet thick, that are tens of feet long. He believes that they are reworked inclusions of schist.

Correlation. The various bodies assigned to the Bethlehem gneiss are correlated on the basis of lithologic similarity. Although the extreme varieties of the Bethlehem are very dissimilar in appearance, largely because of differences in the intensity of the foliation, the existence of all gradations indicate the unity of these rocks. Moreover, as will be shown in the section on structure, there are reasons to believe that several of the larger bodies belong to a single intrusion.

C. H. Hitchcock correlated much of what is here called Bethlehem gneiss with the "Lake Winnipiseogee gneiss." There is considerable justification in doing this, because texturally and mineralogically the two rocks are alike. However, the average Bethlehem is a granodiorite approaching a quartz monzonite in composition, whereas the average Winnipesaukee is a quartz diorite. But the similarity indicates clearly that the two rocks belong to the same plutonic series. Likewise, where microcline phenocrysts are present in the Bethlehem gneiss, it closely resembles the Kinsman quartz monzonite; this indicates the consanguinity of these two rocks.

Quartz Monzonite of Norway Rapids

Name. This rock is named from Norway Rapids on Avalanche Brook, 2 miles northeast of Waterville Valley in the central part of the state.

Distribution. The only body of this rock, which lies north of Waterville Valley, is 6 miles long and 1½ miles wide.

Lithology. This is a pink, medium-grained to coarse-grained quartz monzonite with phenocrysts of pink microcline as much as 3 inches long. The principal dark mineral is biotite; other minerals are oligoclase, quartz, and a little muscovite.

Correlation. This rock is very similar to the Kinman quartz monzonite. The two rocks differ only in color, the Kinsman being gray rather than pink.

Kinsman Quartz Monzonite

Name. One of the most striking rocks in New Hampshire, this unit is named from the type locality in Kinsman Notch, 5 miles west of North Woodstock (Billings, 1937, p. 506). A phase that is even richer in phenocrysts of potash feldspar than the rock in the type locality is extensively developed around Lake Winnipesaukee; it has been called the Meredith granite (Billings, 1928, p. 83). Hitchcock (1877, p. 98-104) called it the porphyritic gneiss or porphyritic granite; Daly (1897) also called it the porphyritic granite.

Distribution. The Kinsman is found in eight large bodies, as well as numerous smaller masses. The special names applied to some of these bodies are shown on the structure map accompanying the geological map. The principal areas are:

(1) In the extreme southwest corner of the state a large body forms half an oval. With its northern extremity east of Spofford and its southern end southwest of Winchester, it is 12 miles long and 6 miles wide. (2) The largest body, the Cardigan pluton, is 60 miles long and as much as 12 miles wide; the south end is at West Peterborough whereas the north end is 2 miles north of Groton. Four small bodies lie between Dublin and the Massachusetts state border. Moreover, eight small bodies lie between the main body and the Merrimack River. (3) The Rumney pluton, which extends from north of Rumney to 4 miles east of Woodstock, is an irregular body with numerous branches. (4) The Lincoln pluton, which

extends from 5 miles southwest of Woodstock to 2 miles south of the village of Twin Mountain, is 25 miles long and up to 6 miles wide. Part of this body is isolated by intrusions of the younger White Mountain plutonic-volcanic series. (5) Another large area is around Lake Winnipesaukee, where the Meredith phase of the Kinsman quartz monzonite and the Winnipesaukee quartz diorite collectively constitute the Winnipesaukee pluton. The Kinsman here is shaped like a huge fishhook, with the barb near Meredith and the end of the shaft near the village of Whiteface. The north and south ends are 22 miles apart. Two small areas are respectively 4 miles northwest and 2½ miles west-southwest of the village of Alton Bay at the southeast end of Lake Winnipesaukee. Seven small bodies are also shown north of Squam Lake; the distribution of the rocks here is more complex than can be shown on a map of this scale, or even on a scale of 1 inch to the mile. (6) An irregular body as much as 6 miles long lies east of the village of Waterville Valley. (7) A body 5 miles long southeast of the summit of Mt. Carrigain is cut into two parts by a dike of porphyritic quartz syenite. (8) A body 4 miles long lies 5 miles west of North Chatham.

Lithology. The Kinsman quartz monzonite in the area around Kinsman Notch is a dark-gray, medium-grained to coarse-grained rock that is massive to strongly foliated. The principal minerals are oligoclase-andesine, quartz, potash feldspar, biotite, and muscovite. Although non-porphyritic in places, elsewhere it has phenocrysts of potash feldspar showing Carlsbad twins, from 3 to 5 cm. long. Locally, these phenocrysts constitute 10% of the rock, and exceptionally 10% to 20%. The amount of oligoclase-andesine decreases with an increase in the number of these phenocrysts of potash feldspar. The non-porphyritic phrase averages granodiorite in composition, whereas the porphyritic phase averages quartz monzonite. In general, the rock shows hypidiomorphic granular texture rather than the granoblastic texture that is characteristic of the Oliverian plutonic series and common in the Bethlehem gneiss.

In the northern end of the Cardigan pluton, where the rock has suffered greater deformation, a granoblastic and cataclastic texture is characteristic. Not only does the rock show a coarse foliation, but the phenocrysts of potash feldspar and granulated aggregates of other minerals show a lineation (Fowler-Lunn and Kingsley, 1937).

In the southern part of this body, around Highland Lake, Heald (1950) says that the Kinsman ranges from quartz diorite to quartz monzonite, with granodiorite predominating. The phenocrysts of potash feldspar, composed of microcline-microperthite, are 3 to 7 cm. long, average 10% of the rock, but range from 5% to 25%; they are oriented parallel to one another. The groundmass is hypidiomorphic granular with granoblastic tendencies. Large garnets (almandite), 1 to 3 cm. in diameter, constitute 1% to 5% of the rock, but in many places they have altered to biotite. For several miles near the western contact around Stoddard, cordierite is very common, constituting from 3% to 7% of the rock; much of it is altered to sericite. Sillimanite is also locally present.

The Meredith porphyritic granite in the Lake Winnipesaukee region has been described by Quinn (1944). This light-gray rock contains many Carlsbad twins of potash feldspar, mostly microcline, 2 to 4 cm. long; they are commonly parallel to one another. The groundmass is quartz, oligoclase, biotite, and muscovite; accessories are garnet and sillimanite. Inasmuch as potash feldspar is dominant over plagioclase, the rock is granite.

Slab-like inclusions are ubiquitous in the Kinsman; the more obvious inclusions are a few inches to a few feet or tens of feet long, but mapping in places shows that they may be as much as several thousands of feet long. Originally mica schist, many of the inclusions have been reworked to a rock that resembles the Kinsman quartz monzonite. Where inclusions are especially abundant, as west of Westport in the extreme southwest corner of the state, a special symbol (*kqml*) has been used on the geological map.

In places the Littleton formation and the Kinsman are so intricately entangled that a special symbol has been used on the geological map (*Dlk*). Several such areas are shown north and northwest of Squam Lake. In another locality, 4 miles northeast of Squam Lake, the symbol *Dlkq* is used to show an area in which the Littleton, Winnipesaukee, and Kinsman are associated on such a scale that the individual units cannot be separated on the geological map.

The "Franconia" breccia, shown on the map by the symbol *kqmb*, is described under the binary granite.

Correlation. The various bodies of Kinsman quartz monzonite, including the Meredith granite, are correlated because of

textural and mineralogical similarities. Although the extreme types—the non-porphyritic phase on the one hand and the highly porphyritic phase on the other—differ greatly in the percentage of phenocrysts of potash feldspar, the existence of all transitions between extremes indicates that we are dealing with closely related rocks.

French Pond Granite

Name and Distribution. The French Pond granite is confined to a circular stock 3 miles in diameter 3 miles southeast of Woodsville. The name comes from French Pond, which lies 4½ miles southeast of Woodsville.

Lithology. The French Pond granite is a heterogeneous rock composed of five different phases (Billings, 1937, p. 508-509; White and Billings, 1951, p. 663). (1) The porphyritic phase is pink, containing phenocrysts of potash feldspar 1 or more cm. long set in a medium-grained groundmass composed of quartz, oligoclase, and some biotite. (2) With an increase in the abundance of the phenocrysts the porphyritic phase becomes a coarse pink phase. (3) A third phase is a pink, medium-grained subporphyritic granite composed of phenocrysts of potash feldspar, up to 6 mm. long, set in a groundmass of quartz, albite, and muscovite. (4) A gray, medium-grained phase consists of potash feldspar, oligoclase, biotite, quartz, and a little muscovite. (5) An aplitic phase, which cuts the other granites and the surrounding formations, is a fine-grained, pink rock composed of potash feldspar, albite-oligoclase, quartz, and muscovite.

Granite of Hedge Hog Hill

Name and Distribution. This granite, 4 miles northeast of Littleton, is confined to a single body that is 4 miles long and 3 miles wide. The locality name comes from Hedge Hog Hill in this same area.

Lithology. A detailed description of this granite has not yet been published. Robert Arndt (personal communication) says that it is a pink, medium-grained to coarse-grained biotite granite and biotite-quartz monzonite.

Binary Granite

Names. Various names have been applied to the binary granites in New Hampshire. Hitchcock (1877, Vol. 2, p. 112) called them Concord granite because of the superb exposures in the quarries around the state capital. In the southwestern part of the state around Fitzwilliam, Emerson (1917, p. 238) called it Fitzwilliam granite. In the region around Franconia the binary granite was called the Bickford granite because of exposures on Bickford Mountain, 4 miles east-southeast of Franconia (Williams and Billings, 1938, p. 1023-1024). This name has also been used in the Mt. Washington region. It now seems certain that all these granites are not only lithologically similar but are also contemporaneous. They could all have been designated Concord granite on the map.

Distribution. These rocks are widespread throughout the state, but generally form relatively small bodies. In many places the boundaries are difficult to map. A body of granite that is a mile or so across may be surrounded by a zone many hundreds or thousands of feet wide where the older country rock is intricately injected by dikes and sills of binary granite. Elsewhere, what at first appears to be a body of homogeneous binary granite, on detailed mapping turns out to be an area of older country rock injected by large and small dikes and sills of binary granite. This complication is further aggravated by a lack of complete exposure. Consequently, the shape of these bodies of binary granite on the geological map is in many places somewhat arbitrary.

The binary granites are found in the following places:

(1) One area where the binary granites are abundant is in the southwest corner of the state in the vicinity of Keene. Half a dozen bodies occupy a band 20 miles wide extending from Sullivan on the north to Fitzwilliam on the south. (2) Several bodies lie east and northeast of Sunapee Lake. (3) A large arcuate body southwest of Mt. Cardigan is over 7 miles long. It lies between the Kinsman quartz monzonite on the east and the Littleton formation on the west; the contacts are not clearly defined because many dikes and sills of the Concord intrude the older rocks. (4) A large body around Newfound Lake is nearly 16 miles long. Several satellitic bodies lie to the west. (5) A small body lies 4 miles northwest of Waterville Valley. (6) There are a number of bodies in a band 38 miles long and 6 miles wide that extends east-northeast from Franconia to the Maine border. (7) A large body in Coös County north of Percy is 10 miles long; it has never been carefully studied. (8) Two miles southeast of Dixville Notch

there is a body several miles long. (9) Along the Maine border around South Chatham a poorly exposed body is about 10 miles long. (10) There are two bodies near Bartlett, one 3 miles to the north of the village, the other 5 miles to the south. (11) There are several bodies in the area east and southeast of the Ossipee Mountains; exposures here are very poor and what appears to be the largest body may actually contain many areas of schist. (12) There are half a dozen bodies within 10 miles of Concord, the largest of which is 6 miles long and 3 miles wide.

Lithology. The binary granites are fine-grained to medium-grained, locally coarse-grained, rocks that are light-gray to white. Generally equigranular, they are locally subporphyritic. The principal minerals are potash feldspar, quartz, and oligoclase, with small but conspicuous amounts of biotite and muscovite. The texture is hypidiomorphic granular. In most instances the rock is unfoliated and not banded, but locally a slight increase in the biotite content in bands an inch or so thick may be observed. In the granite at Concord, Fitzwilliam, and Milford, the oligoclase and potash feldspar are present in nearly equal amounts (Chayes, 1952, p. 224). Strictly speaking, therefore, the rock is a quartz monzonite.

In the vicinity of Concord this granite is fine-grained to medium-grained, with an average grain size of 5 mm., but some phenocrysts of potash feldspar are over 1 cm. long (Dale, 1923, p. 196). In the body northwest of the Presidential Range the granites range from fine-grained to coarse-grained rocks; in the latter the feldspars are 3 to 15 mm. long, although the quartz and mica are only 1 to 3 mm. in diameter.

Correlation. The various bodies of binary granite are considered to be of essentially the same age for the following reasons: (1) they are all mineralogically similar; (2) in general, they lack deformation except for minor strain shadows in the quartz; and (3) these granites all intrude the adjacent country rock in a similar way, sending off irregular dikes and sills.

"Franconia Breccia"

Two bodies of "Franconia breccia" (*kqmb*) are shown on the geological map, 6 and 10 miles north of North Woodstock. Hitchcock (1877, p. 137-142) proposed the locality name from Franconia Notch, where the rocks are well exposed. Inasmuch as

Franconia is now used as a sub-division of the Upper Cambrian in the upper Mississippi Valley, it seems best to abandon Franconia as a formation name in New Hampshire, even though it has priority.

"This breccia consists of angular fragments of Kinsman quartz monzonite and older schists in a light-colored, fine-grained granitic matrix . . . . The inclusions range from a few inches to several feet in diameter. The matrix is a light-colored, fine-grained binary granite. In the central part of the body the granite constitutes 50 per cent of the breccia, but it becomes progressively less abundant near the margins" (Williams and Billings, 1938, p. 1024). It is apparent that the Franconia breccia is a plutonic breccia, the matrix of which is binary granite.

Pegmatites

Large bodies of pegmatite are associated with the New Hampshire plutonic series, especially with the binary granites. They have been described in great detail by Bannerman (1943), Olson (1942,1950) and Cameron et al (1945, 1954). They range in size from bodies a few feet long and a few inches thick to those that are thousands of feet long and hundreds of feet thick. They are generally white pegmatites composed of white microcline, oligoclase, biotite, and muscovite.

Relative Ages

There are two ways to determine the relative ages of the various members of the New Hampshire plutonic series. One method is by cross-cutting relations; that is, dikes of the younger rock cut the older rock, or inclusions of the older rock are found in the younger rock. A second method is by the intensity of the deformation; that is, the extent to which a rock shows cataclastic texture, granoblastic texture, secondary foliation, secondary lineation, or recrystallization. This second method is fraught with difficulty because the intensity of deformation may depend on location as much as on age. That is, two originally similar rocks of the same age may be subjected to later deformation, but one is in a zone where movements are concentrated, whereas the other is in a block between zones of intense deformation.

The four major rocks with which we are concerned are quartz diorite, Bethlehem gneiss, Kinsman quartz monzonite (including the quartz monzonite of Norway Rapids), and binary granite.

The binary granites are the youngest. They are least deformed of these four major groups; the texture is generally hypidiomorphic granular, whereas the others, although in places showing a hypidiomorphic granular texture, more commonly display a granoblastic or cataclastic texture. Secondly, whereas the quartz diorite, Bethlehem gneiss, and Kinsman quartz monzonite show signs of having been involved in the regional metamorphism, the binary granites are unmetamorphosed. Thirdly, and what is most significant, the binary granites contain inclusions of some of the other types. That the binary granites cut the Kinsman is clear from the description of the "Franconia breccia." Also, in the Mt. Cardigan and Mt. Monadnock areas, the binary granites cut the Kinsman (Fowler-Lunn and Kingsley, 1937, p. 1371; Fowler-Billings, 1949, p. 1270). The quartz diorites are also older. In the Monadnock region, the binary granites cut the Spaulding quartz diorite (Fowler-Billings, 1949, p. 1270). In the Gorham area (Billings and Fowler-Billings, unpublished data) the binary granites also cut the quartz diorite.

The mutual age relations of the Kinsman, Bethlehem and quartz diorites are not clearly shown. In the Littleton-Moosilauke area Billings (1937) concluded that the Bethlehem was older than the Kinsman, inasmuch as it is generally more strongly foliated and has a more intensely developed granoblastic texture.

The quartz diorites are shown on the explanation of the map as older than both the Bethlehem and the Kinsman. Daly (1897, p. 707-710) concluded that the "Lake Winnipeseogee gneiss" was older than the "porphyritic gneiss" (Meredith phase of the Kinsman under the present classification). But Quinn (1944, p. 477) reached the opposite conclusion, and in the Monadnock region Fowler-Billings (1949, p. 1268) also concluded that the Spaulding is younger because it is less foliated than the Kinsman.

The undeformed character of the French Pond granite and the granite of Hedgehog Hill indicate that they are relatively late in the sequence.

Plutonic Rocks of Southeastern New Hampshire (Hillsboro Plutonic Series)

General Statement

The plutonic rocks of southeastern New Hampshire—that is, southeast of the northwest border of the Fitchburg pluton—are shown on the geological map by a distinctive set of color patterns in various shades of orange. As indicated on a previous page, these rocks may be grouped together as the Hillsboro plutonic series, but this name has not been used on the geological map. Although these rocks have many features characteristic of the New Hampshire plutonic series, they are separately shown because they may be a different age. Four units are shown: (1) diorite and granodiorite; (2) granite, quartz monzonite, and granodiorite; (3) Ayer granodiorite; and (4) granite.

Diorite and Granodiorite

Distribution and Names. Half a dozen bodies of diorite and granodiorite are shown north of the Massachusetts border in the vicinity of Nashua between Hollis and Atkinson. On the geological map of Massachusetts and Rhode Island (Emerson, 1917), some of these bodies are called Dracut diorite, from the type locality at Dracut, Massachusetts. A large body extending northeast for 20 miles from Exeter to Dover has been called the Exeter diorite. This official designation by the U. S. Geological Survey is preserved, although the rock has an average composition of a granodiorite. Three small bodies are shown around Kensington, but the mapping here is very arbitrary because of the reconnaissance nature of the survey and the poor exposures.

Lithology. In New Hampshire only the Exeter diorite has been studied in detail. Professor T. R. Meyers, State Geologist of New Hampshire, has kindly furnished the author a copy of a report on a petrographic study of the Exeter diorite by Ruth H. Johnson (1935). The rock is everywhere hypidiomorphic granular, with the grains generally 1/8 to 1/4 inch across, although locally biotite flakes are as much as 1/2 inch in diameter. Three miles northwest of Exeter, the rock is gabbro composed chiefly of labradorite and augite, with small amounts of chlorite, biotite, quartz, and minor accessory minerals. Around Durham, the rock is granodiorite composed of andesine, hornblende, biotite, microcline, quartz, and some pyrite. Two miles east-southeast of Durham it is quartz monzonite, composed of microcline, oligoclase, quartz, biotite, and hornblende.

Granite, Quartz Monzonite, and Granodiorite

Distribution and Name. The rocks mapped under this designation, which are assigned to the Fitchburg pluton on the structure map, extend for 75 miles across the state from Brookline

and Mason near the Massachusetts border to the vicinity of Rochester near the Maine border. This is a continuation of what Emerson (1917) mapped as Fitchburg granite in Massachusetts. It should be emphasized, however, that the Fitchburg granite on the geological map of Massachusetts and Rhode Island (Emerson, 1917, p. 232-233) includes two very different rocks. The Fitchburg granite in the narrower sense was used by Emerson for a light-colored, medium-grained binary granite that is essentially the same as the Concord granite of New Hampshire. But on his map, Emerson included a medium-grained, dark-gray biotite granite that is somewhat banded because of the concentration of biotite in layers. Thus, most of the Fitchburg pluton in New Hampshire does not consist of the true Fitchburg granite, but rather is composed of the granodiorite that was included with the Fitchburg on Emerson's map.

Lithology. Detailed descriptions are available only for that part of the Fitchburg pluton in New Hampshire around the Pawtuckaway Mountains, where Freedman (1950) mapped three major lithologic types. These types are similar in several respects: (1) they are medium-grained to coarse-grained rocks; (2) foliation, although absent in some places, is elsewhere weak to strong; and (3) biotite is the principal dark mineral, although locally it may be accompanied by hornblende or muscovite. The strike of the foliation is not very systematic, although northeasterly trends seem to be most common. The quartz monzonite, which is light-gray to dark-gray, is composed of potash feldspar (both orthoclase and microcline), oligoclase-andesine, quartz, biotite, and some hornblende. Biotite averages about 11% of the rock, whereas hornblende averages about 3%. A biotite-muscovite granite, which is white to light-gray, is composed chiefly of potash feldspar, calcic oligoclase, and quartz; biotite and muscovite each constitute about 4% of the rock. The microcline granite, which is light-gray to pink, consists chiefly of pink microcline and quartz; biotite and muscovite each constitute about 4% of the rock; a small amount of calcic oligoclase is present. Pegmatites, ranging from small dikes to bodies 450 feet long and 50 feet wide, are common. They are composed chiefly of perthite and quartz, with small amounts of garnet, biotite and muscovite.

Freedman (1950, Plate 1) implies that each of these types covers many square miles, although he states that the quartz monzonite and muscovite-biotite granite grade into one another.

Several large septa or roof pendants of the Littleton formation lie within the plutonic rocks.

Ayer Granodiorite

Name. The locality name comes from Ayer, Massachusetts, 15 miles south-southwest of Nashua. Emerson (1917, p. 223-228) called the rock a granite, but Jahns has classified it as granodiorite (1952).

Distribution. The Ayer seems to have been reluctant to enter New Hampshire, for it is found only within a few miles of the Massachusetts border. Nearly a dozen bodies, all relatively long and narrow, trend northeast between Nashua and Plaistow. Two other small bodies are shown in the extreme southeast corner of New Hampshire.

Lithology. In the southeast corner of New Hampshire the Ayer is a porphyritic granite; phenocrysts of potash feldspar from 1 to 3 inches long are set in a medium-grained to coarse-grained groundmass composed of plagioclase, quartz, biotite, and muscovite. This phase of the Ayer is similar to, if not identical with, the Kinsman quartz monzonite. Detailed descriptions of the other bodies of the Ayer granodiorite shown on the geologic map are not available.

Correlation. The isolated bodies of Ayer granodiorite are correlated with one another and with the rocks in the type locality on the basis of lithologic similarity and consanguinity.

Granite

Distribution. The rocks mapped as granite in southeastern New Hampshire, all in relatively small bodies, are shown in four areas. One area is a belt 8 miles wide just north of the Massachusetts border, extending from Mason on the west to Pelham on the east. The second area is in the northeastern part of the city of Manchester. A third area is a belt 6 miles wide along the New Hampshire coast. The Isles of Shoals constitute the fourth area.

Lithology. These granites are all similar in being light-gray to white, medium-grained binary granite and quartz monzonite. But some are massive, unfoliated rocks, whereas others are strongly foliated. The massive type is well represented in the small bodies around Milford, where excellent exposures may be

seen in the granite quarries. These massive granites are similar to the Concord and other binary granites found further northwest in the state. In places biotite is more abundant in bands 1 inch wide than in the intervening layers; Dale (1923, p. 180-191) quite correctly interpreted these layers as flow banding. Where present near the contact with the older country rocks, these bands are parallel to the contact, even though the contact may be locally rather irregular. The bands are not parallel to the structure in the older rocks. In those granites that are strongly foliated the foliation strikes northeast and dips steeply, parallel to the regional structure.

Relative Ages

The relative ages of these groups of plutonic rocks in southeastern New Hampshire are not well established. The rock mapped as granite is certainly younger than the rocks in the Fitchburg pluton that are mapped as granite, quartz monzonite, and granodiorite; this is superbly shown, for example, in the quarries around Milford. It is probable that the foliated binary granite is older than the massive binary granite. In Massachusetts Jahns (1952, p. 112) has given a sequence similar to that adopted on the geological map of New Hampshire.

Mississippian (?)

White Mountain Plutonic-Volcanic Series

General Statement

The White Mountain plutonic-volcanic series derives its name from the White Mountains, where it is extensively developed. Some of the magma erupted on the surface as lava flows and pyroclastic rocks to form the Moat volcanics. Much of it consolidated beneath the surface to form plutonic rocks, which have been classified into fourteen units on the geological map. Some of the magma consolidated to form small intrusive bodies, which are shown on the map under three designations—rhyolite, volcanic rocks, and camptonite.

The White Mountain series has certain features that distinguish it from the older plutonic series. In general, the rocks are massive and seldom show foliation or banding; the only exceptions are some banded mafic rocks. Texturally the White Mountain series is characterized by a hypidiomorphic granular texture, in contrast to the granoblastic texture typical of some of the older rocks. Mineralogically, the White Mountain series is characterized by the persistence of amphiboles, pyroxenes, and even olivines into the syenites and granitic rocks; muscovite is absent. Finally, pegmatites, which are so commonly associated with the Oliverian, New Hampshire, and Hillsboro series, are very rare in the White Mountain series.

Average modes are given in Table 9.

Gabbro

Distribution. The gabbro is confined to relatively small bodies, eight of which are shown on the geological map. These areas are as follows: (1) 14 miles southeast of the Ossipee Mountains; (2) 8 miles east of the southeast end of Lake Winnipesaukee, that is, 3 miles north-northwest of the village of Union; (3) 6 miles northeast of Laconia; (4) at the western base of Mt. Tripyramid, on the southwestern side of the White Mountain batholith; (5) 5 miles south-southwest of the summit of Mt. Washington; (6) 5 miles northeast of Wentworth; (7) 4 miles east-southeast of Wentworth; and (8) 2 miles southeast of Wentworth.

Lithology. As indicated in the explanation for the geological map, the rocks mapped as gabbro are rather heterogeneous, even within individual bodies.

The area 3 miles north-northwest of Union was mapped by Quinn and Stewart (1941) as diorite-gabbro. The rock, generally massive but locally foliated, is a gray to dark-gray rock in which the minerals range from 1 mm. to 4 mm. in diameter. The principal phases are a dark pyroxene gabbro (Table 9, column 1d), hornblende gabbro (Table 9, column 1e), and granodiorite. A breccia in the southwestern part of the body has not been separately distinguished on the geological map; it consists of angular inclusions of diorite and schist a few inches to several feet across, surrounded by a fine-grained phase of the Conway granite.

The body 6 miles northeast of Laconia was called the Gilford gabbro by Modell (1936), from the township with that name. The groundmass is composed of an ophitic intergrowth of labradorite and augite in crystals 1 to 3 mm. long. Large spheroidal crystals of hornblende, about 3 cm. in diameter, poikilitically enclose crystals of labradorite.

The gabbro on the west flanks of Mt. Tripyramid has been

described by A. P. Smith (1940). This body, like the other gabbroic masses, is heterogeneous. Most of the rocks are coarse-grained to medium-grained, massive, dark-gray rocks. The principal phases are olivine-pyroxene gabbro, olivine gabbro, pyroxene gabbro, and pyroxene-hornblende gabbro (Table 9, columns 1a, 1b, 1c, and 1d). Anorthosite (Table 9, column 1f) is not abundant.The south end of the body west of Mt. Tripyramid (Table 9, column 2c) is medium-grained, hypersthene diorite.

The body 5 miles south-southwest of the summit of Mt. Washington has been described by Henderson (1949). The principal type is a dark-green, medium-grained olivine-pyroxene gabbro with ophitic texture, A less common phase is biotite-hornblende gabbro, which contains dark-colored bands about ½ to 6 inches thick that are richer in the dark minerals.

The three bodies near Wentworth are medium-grained to coarse-grained, ophitic, dark-gray gabbro composed of labradorite, pyroxene, amphibole, and biotite (L. R. Page in K. Fowler-Billings and L. R. Page, 1942).

Diorite

Distribution and Name. Diorites belonging to the White Mountain plutonic-volcanic series are shown in four places: (1) Pawtuckaway Mountains in the southeastern part of the state; (2) Belknap Mountains on the southwest side of Lake Winnipesaukee; (3) 4 miles northeast of North Conway; and (4) 3½ miles south-southeast of Franconia.

Lithology. The diorites, like the gabbros, are a somewhat variable group. In the Pawtuckaway Mountains the western two-thirds of the diorite body is chiefly hornblende diorite (Roy and Freedman, 1944). It is a dark, coarse-grained, equigranular rock with some hornblende grains 1 cm. long. The principal minerals are andesine, hornblende, and biotite, with small amounts of hypersthene and olivine (Table 9, column 2a). In the eastern one-third of the diorite body the rock is mineralogically similar, but is foliated because of the parallelism of the plagioclase tablets. Moreover, the feldspar, which is andesine and labradorite, is more calcic than in the unfoliated type in the western part of the body. Chemical analyses of the foliated hornblende diorite indicates that it is not unlike the gabbros described above. The foliation dips inward toward the center of the body. Less abundant varieties mapped as diorite are porphyritic diorite, porphyritic gabbro, augite diorite, and hornblende-biotite diorite (Roy and Freedman, 1944).

The area mapped as diorite in the northern part of the Belknap Mountains is actually a breccia composed of angular fragments of diorite intruded by biotite granite and syenite (Modell, 1936). The blocks of diorite range in size from a few inches to tens of feet in length and, in exceptional cases, to several hundred feet. Modell described this rock as the Endicott diorite, the locality name being taken from Endicott Hill in the center of the Belknap Mountains. The most common rock is a dark, fine-grained diorite in which the grains are about 1 mm. in diameter, but there are also coarse-grained varieties, in some of which the hornblende crystals are over 2 cm. long. The principal minerals are andesine, hornblende, and biotite; the chief minor constituent is augite (Table 9, column 2b).

The diorite 4 miles northeast of North Conway has likewise been shattered and soaked by the Conway granite (Billings, 1928, p. 102). A medium-grained to fine-grained gray to black granular rock, the principal minerals are andesine (some specimens have cores of labradorite that pass progressively outward into a shell of oligoclase), hornblende, and biotite. Much of the diorite has been altered, however, by the metasomatic introduction of pink grains of microperthite derived from the Conway granite.

The small body 3½ miles south-southeast of the village of Franconia is quartz diorite. It is a dark, massive, equigranular rock composed chiefly of andesine, with important amounts of biotite, quartz, and hornblende (Table 9, column 2d). Four miles to the southeast of this body, a small mass of syenite is shown on the geological map; along the east margin of this syenite an area of diorite is too small to be shown on the geological map.

Monzonite

Distribution. Rocks shown as monzonite on the geological map occur in three localities: (1) Pawtuckaway Mountains; (2) two bodies on the north and south flanks, respectively, of the Belknap Mountains; and (3) Mt. Tripyramid.

Lithology. In the Pawtuckaway Mountains an outer incomplete ring and a small central stock less than a mile in diameter are both composed of monzonite. The outer ring is a light-gray to

dark-gray, coarse-grained, equigranular rock composed of oligoclase (locally andesine), potash feldspar (orthoclase and microcline), hornblende, biotite, and augite. A syenitic facies has more than twice as much potash feldspar as oligoclase and has fewer dark minerals. The central stock is composed of both coarse-grained and fine-grained monzonite. These rocks in the central stock are mineralogically similar to those in the outer ring.

The large body of monzonite on the south flanks of the Belknap Mountains was mapped by Modell (1936) as the Gilmanton monzodiorite (Johannsen, 1931-1938, Vol. I, p. 143). The locality name is from the township of Gilmanton, in the northeast portion of which most of the body lies. On the geological maps of the Winnipesaukee and Gilmanton quadrangles it has been called augite monzodiorite. The texture is rather variable, but the most common variety is a medium-grained, equigranular to subporphyritic, light-gray to gray rock composed of oligoclase, microperthite, augite, hornblende, and a little quartz (Table 9, column 3a). The grain size ranges in different localities from 1 mm. to as much as 3 mm.

The very small body of monzonite on the shore of Lake Winnipesaukee was called Ames monzodiorite (Modell, 1936), from Ames Station on the now abandoned railroad. This rock is a medium-grained, gray monzodiorite composed of andesine, microperthite, hornblende, biotite, and a little quartz.

The rock shown as monzonite on Mt. Tripyramid consists of four separate arcuate or circular bodies (A. P. Smith et al, 1940). As shown in Figure 15, diagram F, the innermost ring, about 1,200 feet wide, is composed of monzodiorite, a light-gray, medium-grained, highly feldspathic rock composed chiefly of andesine, but with about 15% microperthite, 4% titaniferous magnetite, 3% biotite, and 2% hornblende. The pink monzonite, which encompasses about 270° of the circumference of the stock, is only about 135 feet wide. It is a pink, fine-grained monzonite that is mineralogically like the monzodiorite except that it has more microperthite and less andesine; moreover, it has about 6% hornblende. Outside the ring of pink monzonite is a gray monzonite, which likewise encompasses 270° of the stock, but is 200 to 1,300 feet wide. It is a light-gray, medium-grained monzonite that is mineralogically very similar to the pink monzonite. The outermost ring encompasses about 210° of the area, but it is absent on the east side of the stock; it averages about 250 feet in thickness, but locally is as much as 500 feet thick. The rock is a dark-gray, fine-grained, porphyritic quartz monzonite. The phenocrysts are hornblende, augite, and plagioclase set in a groundmass composed of oligoclase, quartz, and small quantities of biotite and hornblende; quartz constitutes about 10% of the rock. On the east side of Mt. Tripyramid a screen of basalt, 30 feet wide, is exposed at one locality between the quartz monzonite and the gray monzonite (A. P. Smith, 1940, p. 119-120).

Granodiorite

Distribution. The granodiorite occurs as four small bodies on the northwest, north, and southeast sides of the Merrymeeting stock east of the southeast end of Lake Winnipesaukee.

Lithology. The granodiorite is a gray to dark-gray, fine-grained rock composed chiefly of andesine, with lesser amounts of amphibole, biotite, microperthite, and quartz (Quinn and Stewart, 1941).

Quartz Monzonite

Distribution. Quartz monzonites are shown in two areas. Two small bodies lie on the west side of the Merrymeeting stock. Two other bodies are in the Pliny Range, 12 miles west of Berlin in the northern part of the state. The more westerly of these two bodies is an arcuate dike 4 miles long and as much as 1,800 feet wide. The more easterly body is shown on the map as a stock 3 miles in diameter, but on the original map (R. W. Chapman, 1942; Billings *et al,* 1946) the interior portion, 1½ miles in diameter, is shown as completely covered by glacial drift.

Lithology. The quartz monzonite on the margin of the Merrymeeting stock is a gray, fine-grained rock composed of oligoclase, microperthite, quartz and biotite (Quinn, 1953). The rocks mapped as quartz monzonite in the Pliny Range consist of quartz monzonite and granodiorite that grade into one another so gradually that they could not be distinguished on the original map (R. W. Chapman, 1942). The granodiorite, which Chapman called quartz monzodiorite, is a medium-grained, dark-gray, locally porphyritic rock; it is composed chiefly of andesine, hornblende, and orthoclase, with lesser amounts of biotite, pyroxene, and quartz. The quartz monzonite is megascopically similar to the granodiorite but has a higher ratio of potash feldspar and very little pyroxene.

Syenite

Distribution. The syenites are confined to a belt that trends about N. 10° W. from the southeast corner of the state for 135 miles to the west-central part of Coös County. The syenites are found in ten areas. (1) A body in the southeast corner of the state 2 miles northeast of Newton is not over 1,000 feet in diameter. (2) Two bodies in the Belknap Mountains were called the Belknap syenite by Modell (1936). (3) Two ring-like bodies are on Red Hill at the northwest end of Lake Winnipesaukee. (4) A small stock 1 mile in diameter underlies some small hills called The Rattlesnakes just north of Squam Lake. (5) The rocks in the stock 2 miles in diameter 4 miles southwest of the village of Passaconaway in the central part of the state were called the Passaconaway sysnite, from Mt. Passaconaway, by A. P. Smith *et al* (1938). (6) Two bodies of syenite are exposed near Bartlett; one is 2 miles to the west of the village and the other is 3 miles to the southwest. (7) A mass of syenite holds up Mt. Carrigain. (8) A small body lies on the west side of Franconia Ridge. (9) A stock 2 miles in diameter holds up Cherry Mountain 6 miles southeast of Whitefield. (10) Five bodies have been mapped in the vicinity of the Pilot Range; the largest of these is nearly 6 miles in diameter. (11) Two stocks, one on Sugarloaf Mountain, 8 miles northeast of Stratford, the other 5 miles north-northwest of Stratford, have not been studied in detail.

Lithology. The exact shape of the small body of syenite 2 miles northeast of Newton in the southeast corner of the state is not known because detailed field work has not been done in this area. The rock is a fine-grained, light-gray, porphyritic syenite in which orthoclase phenocrysts 3 mm. long constitute 1% of the rock. Microscopic study shows that the groundmass has a grain size of 0.1 mm.; the chief minerals are orthoclase, oligoclase and some quartz. Whatever dark minerals may have been present have been altered to leucoxene and some opaque minerals.

The two arcuate bodies northwest of the Pilot Range, one 3 miles long and the other 1 mile long, are syenite porphyry. The phenocrysts, which are 1 to 8 mm. long, are mostly orthoclase, but there is also some augite. Near the contacts the groundmass is very fine-grained and black, but elsewhere is dark-green and medium-grained. The principal minerals are orthoclase, hornblende, and hedenbergite.

The rest of the rocks mapped as syenite are medium-grained to coarse-grained rocks that are generally green to greenish-gray on fresh surfaces, but locally pink (R. W. Chapman, 1935, 1937; Modell, 1936; Henderson, 1949; Quinn, 1937; Smith, 1940; Williams and Billings, 1938). These rocks are composed chiefly of microperthite, which makes up 80% to 90% of the rock. Locally, some of the potash feldspar is anorthoclase and some is oligoclase. The most common dark mineral, generally from 5% to 10% of the rock, is amphibole, either hastingsite or soda amphibole. Less common dark minerals are hedenbergite, fayalite, and biotite. Quartz averages only a few percent. Aegerine-augite has been reported at Red Hill. Some bodies consist of syenite that is fairly uniform in grain size, but others are composed of syenite that shows a considerable range in grain size and in the ratio of light-colored to dark minerals. On Red Hill, for example, the rock in the outer ring differs considerably in grain size from place to place; generally coarse-grained, in pegmatitic patches the grains are as much as 5 or 6 cm. long. In this same area the inner syenite is a medium-grained, pink, locally gray, rock.

In the Pliny Range, although that part of the stock west of the screens of the Albee formation and the Highlandcroft plutonic series is a fairly uniform, medium-grained syenite, the rock in the main part of the stock shows considerable range in grain size. Coarse-, medium-, and fine-grained types are present; the fine-grained syenite cuts the coarse-grained syenite. Small patches of the rock are porphyritic.

Nephelite-Sodalite Syenite

Distribution. This rock is confined to Red Hill at the northwest end of Lake Winnipesaukee. It forms an irregular ring-like body 2½ miles in diameter and 500 to 5,000 feet wide.

Lithology. The following description is from the paper by Quinn (1937): "The rock is a light-gray, medium-grained rock with crystals ranging from 2 to 10 mm. in diameter but averaging about 4 mm. The feldspar, which is microperthite, is usually lath-shaped and shows Carlsbad twinning. The nephelite is greasy-gray to light brown. The sodalite is greasy-gray, green, or bluish; on weathering these minerals erode more readily than the others, leaving small depressions in the rock. Hastingsite makes up 5% to 10% of the rock. In some places the rock contains aegerine-augite. The amount of nephelite and sodalite differs

considerably in different specimens; together they constitute as much as 35% of the rock, but one may be present to the exclusion of the other."

Quartz Syenite

Distribution and Nomenclature. The quartz syenites are found in eight areas. (1) On the northwest flanks of the Belknap Mountains the rock in a body nearly 2 miles long was called the Sawyer quartz syenite by Modell (1936, p. 1904). On Rattlesnake Island, in Lake Winnipesaukee just north of the Belknap Mountains, he classified the rock as Lake quartz syenite. (2) There are two small bodies on Red Hill; one is ½ mile across, the other is ¾ of a mile across. The more northerly of these was called the Watson Ledge quartz syenite, the more southerly was called the Garland Peak quartz syenite (Quinn, 1937). (3) On Mt. Tripyramid a large stock of quartz syenite, about 1½ miles in diameter, occupies the center of the ring structures. (4) The dike on the southeast slopes of Mt. Carrigain is 1½ miles long and 2,000 feet wide; because of the detail shown in this region, it was necessary to represent this body as less than 2,000 feet wide on the geological map. (5) Quartz syenite, 3 miles south of Bretton Woods, forms a body 1½ miles long and 1,500 feet wide. (6) A large body 10 miles north of North Conway is nearly 4 miles in diameter. (7) Two arcuate bodies have been mapped in the Pliny Range. (8) In the west-central part of the state, 14 miles east of Hanover, a small body, not over 1,000 feet in diameter, is represented by only one outcrop and residual soil.

Lithology. The quartz syenites are medium-grained rocks that in most places are gray or green-gray. In the Belknap Mountains and on Mt. Tripyramid, they are pink. In general, they are equigranular, but near contacts, especially on Red Hill and in the Pliny Range, the rock is locally subporphyritic or porphyritic. The principal mineral is feldspar, which constitutes 80% to 90% of the rock. It is generally microperthite, but the quartz syenites on Red Hill, Mt. Tripyramid and in the Pliny region contain up to 10% oligoclase (ranges in different areas from An_{10} to An_{30}). Amphibole, present in most specimens, averages about 8% of the rocks, but ranges from 0 to 13%. In most localities it is hastingsite, but in the Belknap Mountains it is common hornblende, and on Mt. Tripyramid it is common hornblende pleochroic in shades of brown. In the more southerly of the two bodies on Red

Hill the amphibole forms needles as much as 4 mm. long. Hedenbergite has been found in the quartz syenites north of North Conway and in the Pliny Range. Biotite, absent in many specimens, rarely exceeds a few percent. Quartz generally forms 5% to 10% of the rock, but in the Pliny Range, where it averages 12%, it forms 8% to 19%.

It is apparent that mineralogically the quartz syenites do not greatly differ from the syenites. Although the quartz syenites average 7 % quartz and the syenites average 3% quartz, it is obvious that many individual specimens within the areas mapped as syenite may technically be quartz syenite, that is, have over 5% quartz. Conversely, many of the rocks in the areas mapped as quartz syenite may be technically syenite.

Porphyritic Quartz Syenite

Distribution and Names. The porphyritic quartz syenites, almost invariably in arcuate bodies, are found in the following localities. (1) In the Belknap Mountains an arcuate body of porphyritic quartz syenite is ¾ of a mile wide; there is also a small body one mile west-northwest of the village of Alton Bay. (2) The Ossipee Mountains are surrounded by a complete ring that is 9 miles in diameter and as much as 4,000 feet wide. (3) Six miles west of North Conway, on the west flanks of Moat Mountain, an arcuate mass is, in places, over a mile wide. (4) Two miles north of North Conway is the southeast end of a body shaped like an inverted *S* that is 15 miles long and up to a mile wide. (5) Four small bodies of porphyritic quartz syenite are peripheral to the large body of quartz syenite 10 miles north of North Conway. (6) On the southeast flanks of Mt. Carrigain an arcuate body is 1½ miles long and up to 1,000 feet wide. (7) A large, arcuate body can be followed from a point 4 miles north-northeast of North Woodstock for nearly 20 miles to Crawford Notch.

In all the areas, except those noted below, these rocks have been called the Albany quartz syenite. Hitchcock (1877) long ago recognized that this was a distinctive rock and called it the Albany granite, from the township of Albany, which lies to the west of North Conway, but is not shown on the geological map, inasmuch as there is no village. The rock in the body between Lincoln and Crawford Notch has been called the Mt. Garfield porphyritic

quartz syenite, from Mt. Garfield, 7 miles east-southeast of the village of Franconia (Williams and Billings, 1938).

Lithology. In the most common type of porphyritic quartz syenite, the Albany, phenocrysts average 1/3 of the rock and are mostly feldspar. These phenocrysts are generally euhedral to subhedral crystals 3 to 5 mm. long, but locally they may be as much as 10 mm. long; chiefly microperthite, some are oligoclase or anorthoclase. Quartz phenocrysts, which are less common than feldspar, are 2 to 5 mm. in diameter. The groundmass is speckled by black amphibole crystals set in a light-gray matrix of feldspar and quartz; this feldspar may be pink, white, or gray.

Feldspar constitutes about 75% to 85% of the rock; it is mostly microperthite, but locally includes anorthoclase; oligoclase comprises 15% of the rock in some places. Quartz is 12% to 18% of the rock, whereas hastingsite is 3% to 12%. Hedenbergite and fayalite may be present in amounts less than 2%.

The Mt. Garfield quartz syenite in the arcuate body between Lincoln and Crawford Notch differs only slightly from the Albany; the feldspar phenocrysts are somewhat larger, from 6 to 12 mm. long, and the dark minerals may be slightly less abundant. The rock in the four bodies north of North Conway, called nordmarkite porphyry by Billings (1928), has a black, fine-grained groundmass, but the feldspar phenocrysts are similar in size and composition to those in the Albany.

If 15% quartz is taken as the boundary line between quartz syenite and granite, it is apparent that the Albany and Mt. Garfield are on the border line between the two groups and could be properly placed in either category.

Rhyolite

Distribution. Rocks mapped as intrusive rhyolite are confined to three bodies, all of which lie east of the southeast end of Lake Winnipesaukee.

Lithology. The rhyolites in the two bodies near Copple Crown Mountain have been described by Quinn and Stewart (1941). The rock, which is light-gray, flesh-colored, or pink, is generally porphyritic. The phenocrysts, which are feldspar, biotite, and quartz, are 3 to 4 mm. long and reach a maximum length of 8 mm. The feldspar phenocrysts are microperthite and oligoclase. The groundmass is a fine-grained intergrowth of microperthite, oligoclase, and quartz (Table 9, column 10).

The arcuate body of rhyolite east of Lake Wentworth is described on the legend of the geological map of the Wolfeboro quadrangle (Quinn, 1953) as "light-yellow to light-green, fine-grained, porphyritic, spherulitic rhyolite, which is massive or has flow structure; phenocrysts of microperthite, quartz, and oligoclase."

Although the two bodies near Copple Crown Mountain may be surface volcanics, perhaps part of the Moat volcanics, the rhyoites east of Lake Wentworth appear to be an intrusive sheet that dips southwest (Quinn, 1953, section CC′, geological map).

Granite Porphyry

Distribution and Name. The granite porphyries are exposed in six areas. (1) One is 10 miles east of the southeast end of Lake Winnipesaukee, where there is a stock somewhat over a mile in diameter. (2) A second area is 2 miles west of the village of Alton Bay. (3) Three bodies lie east of Franconia Notch. One of these is a large north-south dike which, because of its resistance, forms the backbone of Franconia Ridge; this dike is 6 miles long and is ¾ of a mile wide. A stock 1 mile in diameter is 4 miles northeast of Mt. Lafayette. The largest body, extending for 10 miles from near Big Coolidge Mountain to Mt. Hale, is as much as 4 miles wide. (4) A small body lies west of Crawford Notch near Mt. Field. (5) Four additional bodies, mostly dike-like, lie 6 miles south of Crawford Notch. (6) An arcuate mass, 8 miles long and as much as 1 mile wide, holds up the Crescent Range north of Randolph.

In the area east of Franconia Notch, these rocks have been called the Mt. Lafayette granite porphyry, from Mt. Lafayette at the north end of Franconia Ridge.

Lithology. The granite porphyries are similar both in mineralogy, texture, and composition to many of the rhyolites in the Moat volcanics. Although most of the bodies classified as granite porphyry are probably intrusive, it is possible that surface volcanics are abundant in the largest of the bodies east of Franconia Notch. Conversely, it is also possible that, locally, granite porphyries are present within the areas mapped as Moat volcanics.

The granite porphyries are pink, gray, green, and red, medium-grained rocks. The phenocrysts, which are chiefly feldspar and quartz, average 2 to 4 mm. in diameter, but some exceed

a centimeter. The phenocrysts of feldspar and quartz are present in about equal amounts and together constitute about 20 to 40 percent of the rock. The feldspar phenocrysts are chiefly microperthite, orthoclase, and anorthoclase, but there is some oligoclase. The quartz phenocrysts are amber-colored or smoky doubly terminated crystals which, in thin section, show considerable resorption.

The groundmass, in which the grains are 0.1 to 0.5 mm. in diameter, is composed chiefly of quartz, microperthite, orthoclase, oligoclase, and a small amount of dark mineral. An average mode is given in Table 9, column 11.

Mt. Osceola Granite

Distribution and Name. One large body of Mt. Osceola granite lies on the south side of the White Mountain batholith, extending as an arcuate mass for 12 miles from north of Big Coolidge Mountain to southeast of Mt. Osceola, from which the locality name has been chosen (Billings and Williams, 1935, p. 15). A second area, about 3 miles in diameter, lies west of Mt. Carrigain. A third, large, very irregular area extends from the south end of Crawford Notch to the western slopes of Moat Mountain. A fourth area, about 5 miles in diameter, centers about Mt. Chocorua in the southern part of the White Mountain batholith. The contacts between the Mt. Osceola and Conway granites are generally gradational, and in some areas the distinction between the two is difficult to make.

Lithology. The Mt. Osceola granite, where fresh, is a greenish-gray, medium-grained to coarse-grained, hypidiomorphic granular rock (Williams and Billings, 1938; Smith, 1940, Henderson, 1949). It weathers white, but is tan where somewhat altered hydrothermally. The feldspar is chiefly microperthite, but sodic orthoclase may constitute as much as 10% of some specimens; a little of the feldspar is anorthoclase. Quartz is smoky or milky-white. An average mode is given in Table 9, column 12. Williams and Billings (1938, p. 1032) have discussed the hydrothermal alteration of the Mt. Osceola: "The primary femag minerals have, in many cases, been hydrothermally altered to chlorite, secondary biotite, secondary hornblende, limonite, and a little pyrite." Henderson (1949) and Smith (1940) do not emphasize such alteration.

Within the Mt. Osceola granite Henderson (1949, p. 58) mapped several units that depend upon the ratio of the dark minerals to one another. He also says that in contact with older schists or gneisses the Mt. Osceola is bordered by a zone of monzonite or quartz syenite that is a few feet to a hundred feet wide.

Hastingsite Granite

Distribution. Hastingsite granite is shown in two localities: (1) 4 miles west of Chatham; and (2) 8 miles west of Berlin.

Lithology. The hastingsite granites are similar in most respects to the Mt. Osceola granite, and it was with some hesitation that the two were separately distinguished on the geological map. The chief difference is that the typical hastingsite granite has more hastingsite and less quartz than the typical Mt. Osceola granite.

In the body 4 miles west of Chatham the hastingsite granite is a greenish-gray, medium-grained to coarse-grained, equigranular rock composed chiefly of feldspar and quartz. The feldspar is chiefly microperthite, but includes about 15% of albite-oligoclase. The quartz is smoky to milky-white. Hastingsite constitutes 8% of the rock. Riebeckite granites within this body have not been separately designated on the geological map. They have been observed in the western part of the body around Doublehead Mountain and also in the southern part of the body. They are similar to the riebeckite granites described below.

The rocks in the body 8 miles west of Berlin have been described by R. W. Chapman (1942) as hastingsite-biotite granite. It is a pink, fine-grained to medium-grained, equigranular to subporphyritic rock, a representative mode of which is given in Table 9, column 13.

Riebeckite Granite

Distribution. Riebeckite granite is shown at four localities on the geological map. One is 2 miles west-southwest of Bartlett on the northern slopes of Mt. Tremont. A second is around Mt. Cabot 8 miles east of Lancaster. A third is 8 miles east of Groveton and a fourth is 3 miles east of Groveton. As previously mentioned, riebeckite granite is also found in the hastingsite granite, 8 miles north of North Conway. Henderson (1949, p. 56) says some riebeckite granite occurs within the area mapped as Mt. Osceola granite in the Crawford Notch area.

Lithology. The riebeckite granites are white, medium-grained granites speckled with black, stubby crystals of riebeckite. Many specimens carry a small amount of elongate sheaves, 1 to 4 mm. long, of golden-yellow astrophyllite. The quartz is clear and vitreous. The texture is typically hypidiomorphic granular. Microperthite is the principal feldspar. A mode is given in Table 9, column 14.

Conway Granite

Distribution. The Conway granite is the most extensive single unit in the White Mountain plutonic-volcanic series. This rock is found in three general areas: (a) south of the White Mountain batholith (see structural map); (b) in and near the White Mountain batholith; and (c) north of the White Mountain batholith.

The Conway granite is found in the following areas south of the White Mountain batholith. (1) One mile west of the village of Alton Bay, at the extreme southeast end of Lake Winnipesaukee, there is a small, arcuate mass of Conway granite. (2) In the Belknap Mountains there is a central stock of Conway granite, as well as two dike-like bodies; much of the area mapped as diorite is a plutonic breccia composed of diorite fragments in a matrix of Conway granite. (3) A stock of Conway granite 6 miles in diameter occupies the center of the Merrymeeting stock at the southeast end of Lake Winnipesaukee. (4) At Red Hill a small central stock consists of fine-grained Conway granite. (5) The center of the Ossipee Mountains consists of a large stock of Conway granite 6 miles in diameter. (6) Green Mountain, 10 miles east of the Ossipee Mountains, consists of a stock of Conway granite 4 miles long.

The largest areas of Conway granite lie within the White Mountain batholith and its satellitic stocks. (7) Within the White Mountain batholith the Conway granite may be assigned to an eastern body and a western body. The western limit of the eastern body is along a north-south line passing through the villages of Bartlett and Pequawket. The western body is much more irregular, but can be approximately described as a broad, arcuate mass convex toward the west, and extending from the village of Passaconaway on the southeast to the village of Twin Mountain on the northwest; an isolated stock is 3 miles south-southeast of Crawford Notch. (8) One of the satellitic stocks peripheral to the batholith is at Cannon Mountain (Profile Mountain) in Franconia Notch. (9) South of this a second stock of Conway granite is in the vicinity of Big Coolidge Mountain. (10) The Mad River stock, 5 miles in diameter, lies south of Waterville Valley. (11) Further east is the stock around Wonalancet. (12) At the northeast corner of the White Mountain batholith a small stock 1 mile in diameter lies 2 miles west of North Chatham.

North of the White Mountain batholith the Conway granite is found in the following areas. (13) Five small bodies are located in the Pliny Range north of Jefferson Highlands. (14) A large northwesterly trending stock 10 miles long lies east of the Pilot Range. (15) A stock 4 miles long includes the Percy Peaks. (16) A large irregular stock 10 miles long includes Goback and Gore Mountains; detailed mapping has not been done in this area.

Lithology. The Conway granite is typically a pink, biotite granite, but it ranges from a fine-grained to a coarse-grained rock. Although some of the maps of individual areas have distinguished various phases, it has not been possible to do this on the geological map accompanying this paper. In general, four major phases may be distinguished. All four phases have been described from the North Conway region (Billings, 1928) and Pilot Range (Chapman, 1935). (1) In the coarse-grained phase, typically exposed in the quarries at Redstone 3 miles south-southeast of North Conway, the pink crystals of microperthite, which commonly show Carlsbad twinning, average about 6 mm. in length, but range from 2 to 6 mm. The quartz grains are somewhat smaller. The biotite flakes average 2 mm. in diameter. (2) In the porphyritic phase, which is very limited in distribution, the feldspar phenocrysts are 5 to 20 mm. in length and the quartz phenocrysts are 2 to 5 mm. in diameter; the minerals in the groundmass are 0.5 to 1 mm. in diameter. (3) In the medium-grained phase the feldspars average 2 to 3 mm. in diameter, whereas the quartz averages about 2 mm. in diameter. (4) In the fine-grained phase the feldspar and quartz range from 0.2 to 1 mm. in diameter.

Near contacts with older rocks the Conway granite shows textural modifications in a zone that is 1 to 10 feet wide. The texture of the rock becomes very heterogeneous, fine-grained granite mingling with porphyries in which the phenocrysts of quartz and feldspar are 2 mm. in diameter (Billings, 1928, p. 121).

Some authors have described small miarolitic cavities

(druses) in the Conway granite (Billings, 1928; Modell, 1936). These cavities, 0.5 to 1 cm. in diameter, are lined with tiny, euhedral crystals of quartz and feldspar. Druses in pegmatites are discussed below.

Volcanic Rocks

Distribution. The rocks classified on the map as volcanic rocks are considered to fill small volcanic vents. (1) Eight miles south of the Pawtuckaway Mountains, in the southeastern part of the state, three small vents lie 2 miles south of Raymond. (2) A larger vent is in the Belknap Mountains. (3) A very small vent lies in the west-central part of the state 14 miles east of Hanover.

Lithology. In the three bodies south of Raymond, the volcanic rocks are rhyolite, quartz latite, keratophyre, andesite, and volcanic breccia. Two of these vents contain considerable gabbro and monzonite (Freedman, 1950, p. 469), but these could not be separately designated on the map because of the scale. The rhyolite is blue-gray where fresh, consisting chiefly of microperthite, quartz, and a little augite and biotite. The quartz latite is also blue-gray, composed of andesine, orthoclase, quartz, and some augite and biotite. The keratophyre, blue-gray where fresh, contains a few phenocrysts of oligoclase, but is chiefly composed of a groundmass consisting of albite; there is also a little quartz, biotite, and amphibole. The andesite is dark-gray to black, composed chiefly of oligoclase and biotite, but these minerals appear to be chiefly secondary. The breccia is composed of angular fragments, ½ inch to 2 feet in diameter, composed of andesite, rhyoite, schist, quartzite, granite, pegmatite, gabbro, and monzonite. The matrix is rhyolite in some places but elsewhere is fine-grained tuff.

The volcanics in the Belknap Mountains, called the Rowes vent agglomerate by Modell (1936, p. 1929), occupy a body 1 mile long and 2,000 feet wide. The agglomerate is composed of rounded to angular fragments a few inches to a few feet across. The fragments are chiefly Kinsman quartz monzonite (Meredith granite phase), but also include quartz syenite, syenite, and Conway granite. The matrix is fragmental, composed of larger grains of feldspar and quartz, from 2 to 10 mm. in diameter, set in a dark, dense groundmass.

The small body 14 miles east of Hanover is not much over 100 feet in diameter (Chapman, C. A., 1939, p. 149). The rock is breccia in which the fragments, as much as a foot across, are composed of Ammonoosuc volcanics, quartz syenite, and quartz diorite; the last has been derived from the Oliverian series. The matrix is composed of large crystals of microcline, microperthite, plagioclase, quartz, and basaltic hornblende set in a dense groundmass.

Camptonite and Other Dike-rocks

Distribution. Dike-rocks comagmatic with the White Mountain series are common in New Hampshire (Billings, 1928, p. 125; Quinn, 1937, pp. 390-394; Fowler-Billings, 1944; Chapman and Williams, 1935, pp. 504, 506; Moke, 1948, pp. 51-73). Most of these dikes are too small to appear on the geological map, but a small body of camptonite, 3 miles east of Charlestown in the western part of the state, covers a sufficiently large area to be shown. This body is a dike that dips gently southward parallel to the hill slope, thus giving considerable breadth of outcrop to a relatively narrow body. It should perhaps be mentioned that the type locality for camptonite is in the central part of the state at Livermore Falls in the township of Campton (Moke, 1948, pp. 66-72; Hawes, 1879; Lord, 1898, p. 343; Rosenbusch, 1886, p. 333).

Lithology. The dike-rocks associated with the White Mountain series include olivine diabase, kersantite, diorite, camptonite, spessartite, augite syenite porphyry, porphyritic syenite, syenite porphyry, bostonite, hastingsite sölvsbergite, paisanite, hastingsite granite, biotite granite, aplite and quartz porphyry.

In the body 3 miles east of Charlestown the camptonite is a medium-grained to fine-grained, dark-gray rock composed of andesine, labradorite, and barkevikite, a brown soda amphibole.

Pegmatites

Pegmatites associated with the White Mountain series are very rare. Gillson (1927) has given a detailed description of a pegmatite in Conway granite in the quarries at Redstone. The pegmatite, which is a vertical dike 1 foot thick, is full of druses, some of which are as much as 18 inches long. The principal minerals are microcline-perthite, quartz, and biotite. Additional minerals are allanite, ilmenite, albite, zircon, fluorite, octahedrite, brookite, sulfides, and carbonates.

A large miarolitic cavity, 5 feet across on the east slopes of

Baldface Mountain 2 miles west of North Chatham, contained large crystals of topaz and phenacite (Billings, 1927).

Locally, other rocks in the White Mountain series are sufficiently coarse-grained to be considered pegmatitic. For example, the syenite on Red Hill in places consists of feldspar crystals as much as 5 or 6 cm. long (Quinn, 1937).

Relative Ages

In the explanation accompanying the geological map the 17 units into which the White Mountain series has been divided are arranged chronologically, insofar as possible. The data on which this sequence is based are summarized in Figure 5. In the left-hand vertical column the rocks are arranged in the presumed proper sequence, with the oldest rocks at the bottom. Similarly, the supposed sequence is also shown in the top horizontal line with the oldest units to the right. The letter symbols within the figure refer to various areas, either quadrangles or regions. The vertical column to the left is the intruding formation, the horizontal column on the top is the intruded formation. Thus, following to the right the horizontal line labelled Conway granite, we find that the Conway is known to intrude the Mt. Osceola granite, rhyolite, porphyritic quartz syenite, etc. The monzonite intrudes diorite, gabbro, and the basalt on Mt. Tripyramid. A heavy jagged line passes diagonally from the upper-left to the lower-right corner. If the sequence is correct and if complete data were available, all the blocks to the right of the jagged line would have letters in them, and, conversely, none of the blocks to the left of this line would have any letters.

The figure shows that data are abundant for some map units. The Conway granite, for example, is known to intrude all the other units except the riebeckite granite and hastingsite granite; but since these last two granites are rather similar to the Mt. Osceola granite, they are presumably older than the Conway. For some units the data are scanty. The granodiorite is not known to intrude any of the other units, but is intruded by the Conway granite. The nephelite-sodalite syenite, although data are scarce, is fairly well bracketed, because it is younger than the syenite but older than the quartz syenite.

A few letters appear to the left of the jagged line. The most significant one indicates that in the Franconia region the porphyritic quartz syenite (Mt. Garfield) intrudes the granite porphyry.

	Camptonite	Volcanic rocks	Conway granite	Riebeckite granite	Hastingsite granite	Mt. Osceola granite	Granite porphyry	Rhyolite	Porphyritic quartz syenite	Quartz syenite	Nephelite - sodalite syenite	Syenite	Quartz monzonite	Granodiorite	Monzonite	Diorite	Gabbro	Moat volcanics	Basalt on Mt. Tripyramid
Camptonite																			
Volcanic rocks			B														P		
Conway granite						F T C	F?	M	N B? C	B L		R I	T L	M	B?	N B	B M	N B	
Riebeckite granite						C			C L			C I	L						
Hastingsite granite									N	N									
Mt Osceola granite							F C?		C?	C		T C?							
Granite porphyry				L?						C							M?	F	
Rhyolite																			
Porphyritic quartz syenite							F			B		B			B?			N B	
Quartz syenite											R	B R	L		T				
Nephelite-sodalite syenite												R							
Syenite						C?									B?	B			
Quartz monzonite																			T
Granodiorite																			
Monzonite																T	T		T
Diorite																			
Gabbro								M?											
Moat volcanics																			
Basalt on Mt. Tripyramid																			

B = Belknap Mtns.
C = Crawford Notch quadrangle
F = Franconia quadrangle
I = Pilot Range
L = Pliny Range

M = Merrymeeting Lake area
N = North Conway quadrangle
P = Pawtuckaway Mtns.
R = Red Hill
T = Mt. Tripyramid

Circle around letters means gradational contact.

Figure 5. Relative ages of plutonic rocks of the White Mountain plutonic-volcanic series. See text for explanation.

This suggests that the granite porphyry should appear below the porphyritic quartz syenite in the explanation. But in the Pliny Range granite porphyry cuts hastingsite-riebeckite granite (Chapman, 1942, p. 1553). Possibly there was more than one injection of granite porphyry. In the Crawford Notch area, although some syenite is cut by the Mt. Osceola granite, elsewhere syenite cuts the Mt. Osceola (Henderson, 1949, p. 64). In the Merrymeeting Lake area (Quinn and Stewart, 1941), gabbro contains inclusions of rhyolite.

GEOLOGIC AGE OF FORMATIONS

General Statement

Although the geological age of some of the strata in New Hampshire can be determined from fossils found within the confines of the state, much of the dating is based on correlation with fossil localities scores of miles away in Quebec, Vermont, Maine, and Massachusetts. Consequently, the discussion of the age of the rocks has been deferred until the descriptions were completed. Moreover, it seems best to follow neither a strictly chronological nor a geographical order in presenting the evidence. Western New Hampshire will be discussed first; this will lead us far afield into Quebec, Vermont, and Massachusetts. Then southeastern New Hampshire will be discussed; this will involve evidence from Maine and Massachusetts. Finally, the reasons for assigning the Moat volcanics to the Mississippian (?) will be discussed.

The problem of dating is difficult for several reasons. First, the number of pertinent fossil localities that can be assigned to a geological period are few, even if we include the adjacent states and Quebec. Secondly, there are numerous instances where forms have been identified as fossils, even given generic and specific names, but which some paleontologists deny are fossils. Thirdly, some specimens are misplaced; although they are perfectly respectable fossils, they did not come from the locality indicated on the label. Uncertainty arises when agreement cannot be reached as to whether or not a specimen is misplaced.

It should be emphasized that dating of the formations is not the same problem as correlating the formations within an area covered by New Hampshire and parts of adjacent states and provinces. This point is made because geologists working in highly fossiliferous formations may confuse the two problems. It is theoretically possible to prepare a stratigraphic column and to map all the formations without any fossils.

The internal correlation within New Hampshire has been discussed in the preceding descriptive sections. Correlation of the metasedimentary and metavolcanic rocks is based on a few fundamental principles. One is the actual tracing in the field of a formation or some subdivision of a formation. For example, the Clough quartzite can be traced continuously from Mt. Cube to Mascoma Lake, a distance of 18 miles; the Post Pond volcanics can be followed continuously from north of Lyme to south of

Claremont, a distance of 40 miles. Secondly, the correlation is based on the recognition of similar sequences of formations, in many cases making due allowance for changes in grade of metamorphism. For example, the strata in the Salmon Hole Brook syncline between Northey Hill and Piermont are correlated with those in the Walker Mountain syncline between Littleton and Woodsville because a stratigraphic sequence consisting of six formations is repeated. This is true not only for the lithology but also for thickness and even for members within formations. Fossils are only of minor importance in correlating the strata within New Hampshire. The author believes that the internal correlation within New Hampshire is reasonably accurate, but not necessarily infallible. Dating the formations is a different problem, but also, in the opinion of the author, reasonably satisfactory. The internal correlation has been considered in previous sections. The age of the formations is considered here.

Western New Hampshire

Silurian

General statement. The Clough quartzite is considered to be Lower or Middle Silurian. The Fitch is known to be Middle Silurian. The Silurian rocks rest with pronounced unconformity on the older rocks. Northeast of Lisbon, where the Clough disappears, the Fitch rests directly on the older rocks.

Fitch formation. The dating of the Fitch formation as Middle Silurian is based on one locality, which is on land that in 1934 was owned by G. E. Fitch; it lies 1.7 miles west-northwest of Littleton (Fig. 6, locality 10). The fauna includes corals, crinoids, brachiopods, trilobites, and bryozoa. A paper by Billings and Cleaves (1934, p. 416-418) describes the fossils in detail. This fauna indicates a Niagaran age. Although fossils were first discovered in the Fitch formation in 1870 (Hitchcock, 1871), this specific locality was discovered in 1873 by C. H. Hitchcock. The age was first considered to be Helderberg, but as early as 1883 it was correctly given as Niagaran (Whitefield, 1883). Less diagnostic fossils have been found in four additional localities in this same belt; a map is given in Billings and Cleaves (1934). The fossils are chiefly corals and crinoids.

Crinoid columnals have also been found in the Fitch formation in slices along the Ammonoosuc thrust southwest of Little-

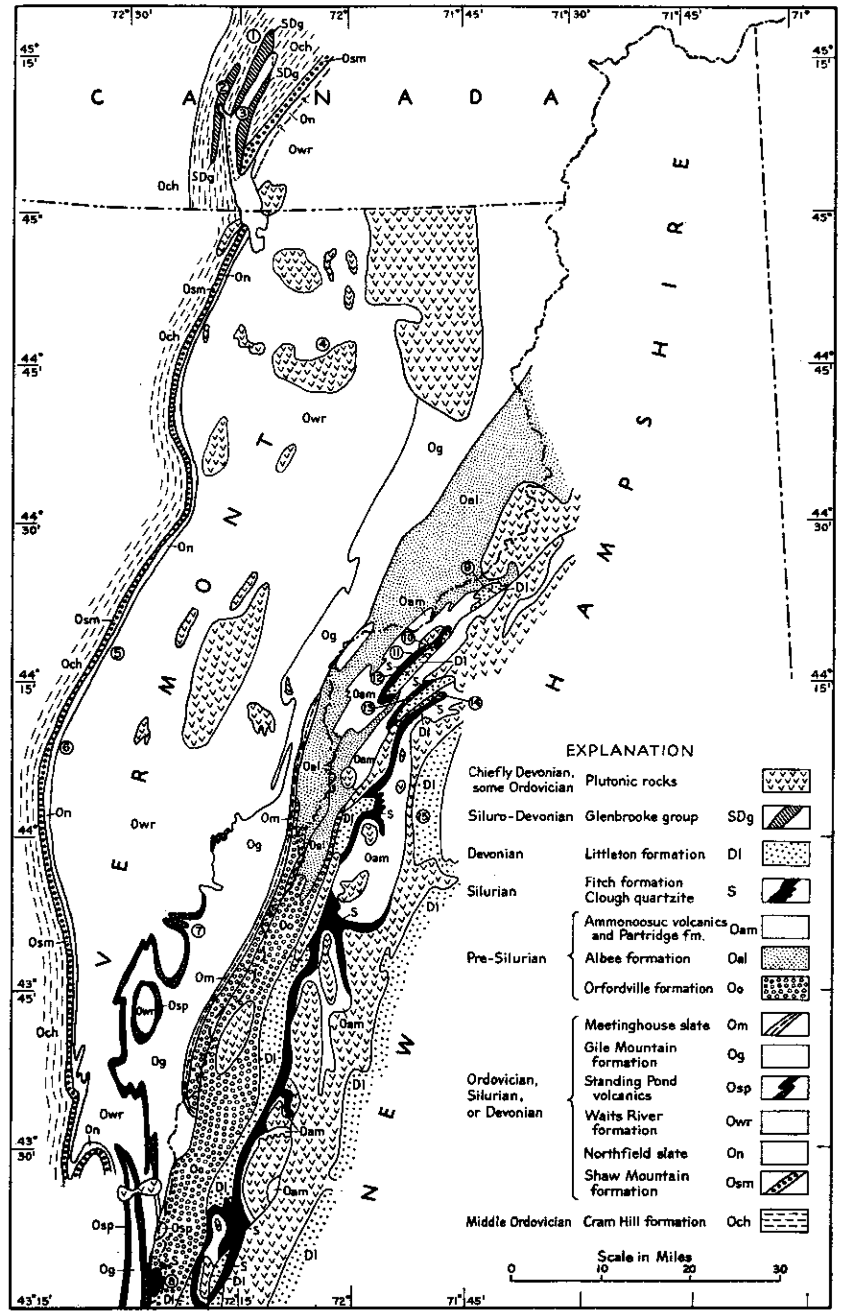

Figure 6. Fossil localities in Vermont and Quebec pertinent to dating some of the rocks in New Hampshire. Numbers in circles are fossil localities; see text for further explanation.

ton in bodies too small to show on the geological map. One of these localities is 2.3 miles west-southwest of Littleton, the other is 1 mile north-northeast of Lisbon.

Another place (Fig. 6, locality 13), along the east bank of the Ammonoosuc River 2 miles northeast of Lisbon, is of especial interest because the rocks are in the staurolite zone. The fossils, which are crinoid columnals and the chain coral *Halysites sp. ind.*, are in a marble associated with amphibolite, mica schist, and actinolite-andesine-quartz granulite (Billings, 1937, p. 486). Crinoid columnals have also been found in the Fitch formation 1 mile west of Franconia (Fig. 6, locality 14; Billings, 1937, p. 486).

Clough quartzite. In the area north of Lisbon the Clough grades upward into the Fitch. Consequently the Clough was considered to be Middle or Lower Silurian. Hadley (1942, p. 130) says that in the Mt. Cube quadrangle the Clough grades laterally into the Fitch, and hence concluded that it must be Middle Silurian.

In 1950, J. B. Thompson and Arthur Boucot discovered fossils in the top of the Clough quartzite on the Vermont side of the Connecticut River 3 miles south-southwest of Claremont (Fig. 6, locality 8). The fauna includes corals, brachiopods, crinoids, cephalopods, and possibly a trilobite (Thompson, 1954, p. 39). Although the rocks are in the staurolite zone, the fossils are sufficiently diagnostic to indicate a Silurian or Early Devonian age (Thompson, 1954, p. 37). They are thus consistent with the Middle or Early Silurian age based on the correlation with the type locality to the north.

Devonian

Littleton area. Fossils were first found in the Littleton formation 2 miles southwest of Littleton by F. H. Lahee (1912, 1913). Billings and Cleaves (1934) later made a more diagnostic collection. The fauna consists of brachiopods, crinoid columnals, and gastropods. The best material was found at two localities, one at Tip Top farm, 3½ miles west-southwest of Littleton (Fig. 6, locality 11), the other at Mormon Hill, 6 miles southwest of Littleton (Fig. 6, locality 12). Less diagnostic material was found at a few other localities in this same belt (Billings and Cleaves, 1934, p. 414). These faunas were considered to indicate an Oriskany age.

Whitefield area. In 1948, R. H. Arndt, A. J. Boucot, K. Fowler-Billings, and the writer collected material from the northeast end of Dalton Mountain 2 miles west-northwest of Whitefield, New Hampshire (Fig. 6, locality 9). Boucot (personal communication) considers the material superior to that found at Tip Top Hill and Mormon Hill; moreover, he believes the age at all three localities is Schoharie rather than Oriskany. The fossils at the Tip Top and Mormon Hill localities occur in strata about 2,500 feet above the base of the Littleton formation, but the Whitefield locality is in strata only a few hundred feet above the base of the formation. Thus the lower 2,500 feet of the Littleton formation is of Oriskany or Schoharie age.

Mt. Clough area. A fossil locality 7 miles southeast of Woodsville is of interest because the fossils are in a mica schist interbedded with sillimanite schists (Fig. 6, locality 15). Only two specimens were found (Billings and Cleaves, 1935). One is a *brachiopod, gen.* and *sp. ind.*; the other is *Spirifer, spec. ind.* Prior to the discovery of the fossils, the enclosing strata had already been correlated with the Littleton formation on stratigraphic grounds.

Bernardston, Massachusetts. Many years ago fossils were found at Bernardston, Massachusetts, which is west of the Connecticut River 4 miles southwest of the extreme southwest corner of New Hampshire. Because the specimens are greatly distorted, the fauna has been variously dated by different paleontologists, some putting it as low as the Middle Silurian, some as high as the Upper Devonian (Whitefield, 1883; Emerson, 1898, p. 259). Schuchert (Schuchert and Longwell, 1932, p. 322) says the fossils are "unmistakable late Lower Devonian." Since the Bernardston and Littleton formations are correlative, this dating by Schuchert is thoroughly consistent with the dating in New Hampshire.

One recent study suggested that the Bernardston formation is Onondaga (Balk, 1942). But it now appears that the guide fossil upon which this dating was based was a mislabelled specimen that actually came from Nova Scotia (A. J. Boucot, personal communication).

Summary. The latest studies indicate that the lower few thousand feet of the Littleton formation are Schoharie in age. On the Devonian correlation chart (Cooper, et al, 1942) the Schoharie is shown as uppermost Lower Devonian or lowermost

Middle Devonian. Since the Littleton formation is 10,000 feet or more thick, it might appear that the upper part contains strata younger than the Schoharie. There are, however, two facts that make this improbable. In central Maine the Schoharie is at least 6,000 feet thick, and perhaps 9,000 feet thick (Boucot, 1953, p. 65). Secondly, recent radioactive age determinations suggest that the New Hampshire plutonic series, which is younger than the Littleton formation, is Middle Devonian.

Ordovician (?)

Orfordville, Albee, Ammonoosuc and Partridge formations. In the Walker Mountain syncline, which lies west of Littleton, the Silurian strata rest unconformably on the Partridge and Ammonoosuc formations. Moreover, the Albee and Orfordville formations are older than the Ammonoosuc volcanics. Hence, from the evidence in western New Hampshire, an upper age limit is established for the Orfordville, Albee, Ammonoosuc, and Partridge formations. But there is no lower age limit. Before making a decision on this matter, it is necessary to range far afield into Quebec and Vermont.

Waits River, Standing Pond, Gile Mountain, and Meetinghouse formations. The stratigraphic sequence in eastern Vermont (Billings et al, 1952) is given in Table 10. All geologists familiar with the area agree that the section is progressively younger from the pre-Cambrian up through the Waits River formation. Moreover, it has been generally assumed that the section continues to be progressively younger up through the Standing Pond, Gile Mountain, and Meetinghouse. This sequence has been assumed to be the correct one in the preparation of the geological map of New Hampshire. Some alternate possibilities will be discussed in a later section.

Currier and Jahns (1941, p. 1500) found crinoid columnals in limestone in the Shaw Mountain formation in the vicinity of Northfield, Vermont (Fig. 6, locality 6). "According to Josiah Bridge (personal communication, 1938) the size and relative abundance of the columnals suggests that the beds cannot be older than the Middle Ordovician, and P. E. Raymond (personal communication, 1940) has concurred with this view. Edwin Kirk (personal communication, 1941) believes the crinoids may be even younger, although they are not generically or specifically determinable (Currier and Jahns, 1941, p. 1500)."

According to Currier and Jahns, the Cram Hill formation may be traced northward to the Canadian border, and it is apparently the same stratigraphic unit as the Magog slate (Clark, 1934, p. 11). At Castle Brook (Fig. 6, locality 1), 3½ miles west of Magog village, the Magog slate contains a graptolite fauna of Trenton age (Cooke, 1950, p. 46-48). Thus the Cram Hill formation appears to be of Trenton (Middle Ordovician) age.

Cady (1950) has found cup corals in the lower part of the Waits River formation north-northeast of Montpelier (Fig. 6, locality 5). Okulitch reported ". . . . my impression is that the corals are probably *Streptelasma.* The genus *Streptelasma* is very common in the Middle and Upper Ordovician of North America. If the specimens are *S. corniculum,* as appears likely, the age could be from Black River to the top of the Trenton."

C. H. Richardson collected numerous specimens from the Waits River formation that R. Ruedemann identified as graptolites, even giving generic, and, in some cases, specific names. The ages were said to range from Beekmantown to lower Trenton. It is now generally agreed (Currier and Jahns, 1941, p. 1505) that these streaks are lineations of tectonic origin. Clark (1934, p. 12) says that graptolites from the Tomifobia formation (Waits River formation) "closely resemble those of the Magog slates . . ." But these specimens are not available for restudy (A. J. Boucot, personal communication). Similarly, Middle Ordovician graptolites reported from this same belt 100 miles northeast of Lake Memphremagog are not available for reexamination (Cooke, 1950).

Doll (1943a) has described fossils from the Waits River formation near Westmore, Vermont (Figure 6, locality 4). The most precise identifications were made by Winifred Goldring, who said: "The crinoid and cystoid types suggest the Silurian." She also said: "The *Platyceras* strongly resembles some of the Devonian forms, but there are Middle Silurian (Niagaran) forms approaching this type." Doll therefore concluded that this part of the Waits River is Silurian, possibly Devonian. However, some paleontologists doubt that the specimens are organic (Doll, 1943a, p. 57).

Doll (1943b) has described a brachiopod from the Gile Mountain formation near South Strafford (Figure 6, locality 7). He identified it as *Spirifer,* probably *murchisoni,* and therefore considered the Gile Mountain formation to be lower Devonian and the equivalent of the Littleton formation.

White and Jahns (1950), as well as White and Billings (1951) questioned the validity of these specimens. Nevertheless, as will be shown below, Doll's interpretation of the age of the rocks may be correct.

We are now prepared to analyze the data given on the preceding pages. In this analysis the Cram Hill formation is considered to be the best-dated unit and to be of Trenton age (Middle Ordovician). Furthermore, it is presumed that the sequence shown in Table 10 is correct; that is, the Meetinghouse slate is the youngest of these formations. Five miles south-southwest of Hanover (Lyons, 1955, Plate 6) the Meetinghouse slate is conformably overlain by the Orfordville formation, which is itself overlain by the Albee, Ammonoosuc, and Partridge formations. But these formations are older than the Middle Silurian, and presumably pre-Silurian, because there is a pronounced unconformity beneath the Silurian. The conclusion from these arguments is that the whole section, from the Cram Hill to the Partridge, is Middle and Upper Ordovician.

Significance of the Glenbrooke Group. An alternate interpretation to that given above, while recognizing that the Orfordville, Albee, Ammonoosuc, and Partridge formations are pre-Silurian, and that the Cram Hill is Middle Ordovician, supposes that the Shaw Mountain is Middle Silurian, that the Northfield, Waits River, and perhaps Standing Pond are Upper Silurian, and that the Gile Mountain and Meetinghouse are Lower Devonian. This is essentially the dating advocated by Doll (1943a, 1943b, 1944) and accepted by the present writer for some years (Billings, 1948).

The Siluro-Devonian Glenbrooke group, preserved in two synclines around Lake Memphremagog in southern Quebec (Fig. 6, localities 2 and 3) has an important bearing on the stratigraphy of Vermont. The Glenbrooke group has been described by Clark (1936), Ambrose (1942, 1943), and Cooke (1950). At the base is the Peasley Pond conglomerate, a quartz conglomerate and quartzite, 140 to 250 feet thick. Above this is a slate, locally calcareous or arenaceous; this slate is 900 feet thick. The rest of the section consists of shale, with some limestone; this unit is 1,600 to 2,100 feet thick (Ambrose, 1942).

Although these rocks are relatively fossiliferous, the preser-

vation is not good. Cooke (1950) concludes that Middle Silurian and Onondaga (upper Lower Devonian) are present. Perhaps the Peasley Pond conglomerate and the 900 foot slate are Middle Silurian, the rest of the section Onondaga. If any Upper Silurian is present, it does not appear to be represented by fossils.

Clark, Cooke, and Ambrose all agree that the Glenbrooke group is not the same as the Northfield and Waits River formations. Since the Glenbrooke ranges in age from Middle Silurian to Onondaga, it follows that the Northfield and Waits River can not be of this age; they must be older or younger. Suggestions that the Shaw Mountain, Northfield, and Waits River range in age from Middle Silurian to Oriskany appear to be untenable.

Alternate Interpretations of Ordovician (?). Although the stratigraphic sequence assumed in the preparation of the geological map of New Hampshire seems most likely, several alternate interpretations cannot be completely eliminated. One of these is given in Figure 7. It assumes that the Shaw Mountain may be correlated with the Clough and Fitch, whereas the Northfield to Meetinghouse, inclusive, may be correlated with the Littleton. This is essentially the correlation accepted by Doll (1943a, 1943b, 1944, 1951) and earlier by Billings (1948). The chief difficulty with this interpretation, as already mentioned, is the fact that the Glenbrooke group of the Lake Memphremagog region, known to be Middle Silurian and Lower Devonian, is unlike the Northfield-Waits River sequence. If the Northfield to Meetinghouse sequence is Devonian, the geological map would have to be modified near Plainfield. The Monroe fault would have to be extended south from where it is shown as ending 6 miles south-southwest of Hanover. Three miles north of Plainfield the east boundary of the Meetinghouse would be the Monroe fault. The boundary between the Gile Mountain and Orfordville at Plainfield would also be the Monroe fault. In other words, the Monroe fault runs into the Ammonoosuc thrust.

A variant of the interpretation given above is that the Waits River is the youngest rock in the section, downfolded in a syncline; the sequence in easternmost Vermont would then be from oldest to youngest, Meetinghouse, Gile Mountain, Standing Pond, and Waits River. These formations would be an eastern facies of the Northfield and a western facies of the Littleton. A corollary of this interpretation would be that a major unconformity exists at the base of the Meetinghouse, which would explain why this

SYSTEM	SERIES	"NEW HAMPSHIRE SEQUENCE"	"VERMONT SEQUENCE"
DEVONIAN	Lower	Littleton	Meetinghouse Gile Mountain Standing Pond Waits River Northfield
SILURIAN	Middle	Fitch	Shaw Mountain
	Lower or Middle	Clough	
ORDOVICIAN	Middle	Partridge Ammonoosuc	Cram Hill
	Middle, possibly older	Albee Orfordville	Moretown Stowe Ottauquechee

Figure 7. Correlation of "New Hampshire sequence" and "Vermont sequence" that is an alternate to that adopted on the geological map of New Hampshire accompanying this report.

formation is in contact with so many different formations (Fig. 6). This interpretation is especially attractive in southeastern Vermont, where the Littleton and Gile Mountain appear to be in contact without any structural break. But this interpretation meets several difficulties. The Standing Pond volcanics should appear along the western contact of the Waits River (Fig. 6). Moreover, the Meetinghouse and Gile Mountain are so much thicker and arenaceous than the Northfield that the proposed correlation seems unlikely.

Numerous observers have been impressed by the lithologic similarity of the Albee and Moretown formations. Moreover, the Ammonoosuc and Partridge are collectively lithologically similar to the Cram Hill. The Orfordville is not unlike the Ottauquechee. If this correlation, as shown in Fig. 7, is correct, the Ammonoosuc and Partridge are Middle Ordovician, whereas the Albee and Orfordville are Middle Ordovician or older.

Summary of Western New Hampshire

The Littleton and Fitch formations are respectively Lower Devonian and Middle Silurian. The Clough quartzite, because it grades vertically and laterally into the Fitch, and because it is above a major unconformity, is Middle Silurian and perhaps also Lower Silurian; fossils at one locality in the Clough are not diagnostic, other than to indicate a Silurian or Lower Devonian age.

The rocks listed on the geological map as Ordovician (?) present a greater problem. The Ammonoosuc and Partridge formations on any reasonable scheme of correlation appear to be Ordovician, but perhaps Middle Ordovician rather than Upper Ordovician. The Albee and Orfordville formations are probably younger than the Middle Ordovician Cram Hill formation, but they may be older. The Waits River, Standing Pond, Gile Mountain, and Meetinghouse formations are probably Middle Ordovician; they may possibly be Silurian and/or Devonian. Because of the uncertainty concerning the age of these formations a query has been placed in parenthesis after the ages given on the geological map.

Southeastern New Hampshire

General statement. Fossils have not yet been found in the Rye formation nor in the Merrimack group (Kittery, Eliot, and Berwick formations). Hence these formations cannot be dated directly by paleontological evidence. Nevertheless, correlation with fossils in distant localities in New Hampshire, Massachusetts, and Maine give some indication of the age.

Previous opinions. Hitchcock (1874) apparently considered the Merrimack group to be Early Paleozoic or Late pre-Cambrian. He makes the following inconsistent statements. "They probably belong to the earliest Silurian series (Hitchcock, 1874, p. 37)." Presumably by "earliest Silurian" he meant what we now call Ordovician. "The occurrence in it of large beds of soapstone, as at Groton, Mass., is suggestive of the Huronian age (Hitchcock, 1874, p. 536)." "These slates are thought to be the equivalents of the Paradoxides beds of Massachusetts (Hitchcock, 1874, p. 536)."

Katz (1917) considered the Kittery and Eliot formations to be Carboniferous, probably Pennsylvanian, on the basis of corre-

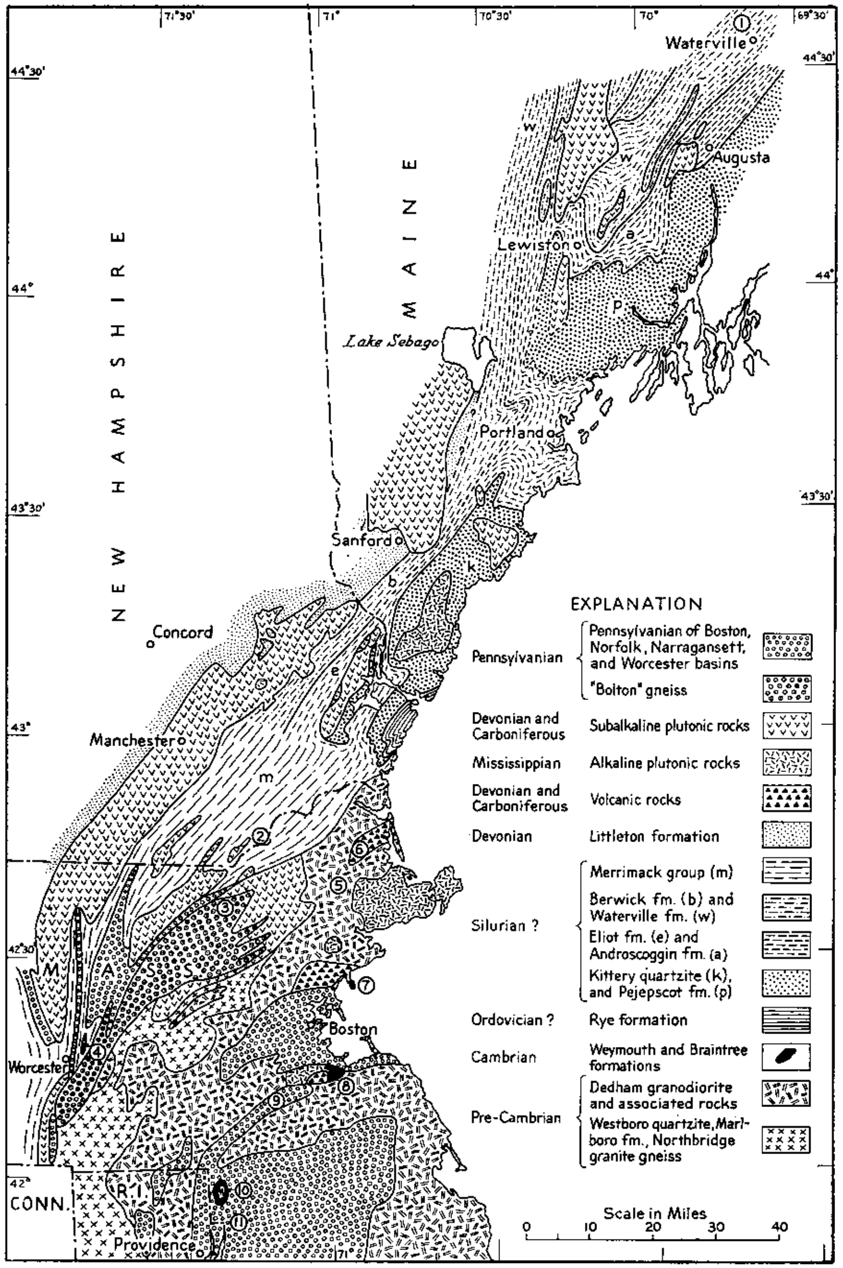

Figure 8. Fossil localities in Massachusetts and Maine pertinent to dating some of the rocks in New Hampshire. Numbers in circles are fossil localities; see text for further explanation.

lation with the Worcester phyllite and Oakdale quartzite near Worcester, Massachusetts. He believed the Rye and Berwick were pre-Cambrian.

Relations of Merrimack group to Worcester phyllite. At the Worcester "coal mine" (Fig. 8, locality 4) in 1883 J. H. Perry found a slab that contained a specimen, 18 inches long, that was identified as *Lepidodendron acuminatum* (Perry and Emerson, 1903). Considerable dispute arose about the significance of this specimen because it might have been shipped to Worcester with coal from Pennsylvania. Judging from the photograph of this specimen (Perry and Emerson, 1903, frontispiece), the present author suspects that this specimen may not be organic; instead, it may be a phyllite with two sets of crinkles intersecting at such an angle as to simulate Lepidodendron.

In 1911 David White (1912) identified fossil plants in the Worcester phyllite (Fig. 8, locality 4). He says: "The specimens at present in hand, though poor and very fragmentary, are such as to put beyond question the Carboniferous age of the phyllite at Worcester . . . Judging by the details of the few pieces collected, the writer suspects that further discoveries will show the beds to be Pennsylvanian, possibly Pottsville." Unfortunately these specimens have been lost for many years. There are so many instances in New England where inorganic material has been called organic, and, as in eastern Vermont, inorganic material even given the generic and specific names of graptolites, that the present writer believes that a reexamination of White's material is desirable. White (1912) recognized the possibility of mistaking inorganic material for organic: "As often happens in graphitic argillites, mineral or cleavage forms accidentally resembling graphitized remains of plants are plentiful. Some of these closely imitate imperfect fragments of Cordaites, Calamites, and Lepidodedron, etc. . . ."

The Worcester phyllite from which these fossils came is preserved in an isolated syncline (Fig. 6, locality 4). Granting the Carboniferous age of these rocks, it is possible that the other belts mapped as Worcester phyllite are older.

Nevertheless, in developing the discussion in the ensuing two paragraphs, it is assumed that the Worcester phyllite is Pennsylvanian and that the large area northeast of locality 4 in Fig. 6 is also Worcester phyllite or a more highly metamorphosed equivalent . Jahns gives the stratigraphic section shown in Table 11 for the Lowell-Fitchburg area of Massachusetts.

The Brimfield schist is considered to be a more highly metamorphosed phase of the Worcester phyllite. "The Harvard conglomerate is truly basal to Emerson's Brimfield schist and contains pebbles that appear to be of Merrimack quartzites" (Jahns, 1941, p. 1911). Thus the Merrimack is Pennsylvanian or older.

Supposed fossil from Lowell. Emerson (1917, p. 59) mentions a specimen 24 inches long in the Geological Museum at Amherst, Massachusetts, that resembles *Calamites cannaeformis* and was labelled "Lowell, Mass." by Edward Hitchcock (Fig. 8, locality 3). On August 14, 1951, M. T. Heald and the present writer found some pseudo-calamites in the Merrimack group. The locality is in the village of Hampshire Road, on the east side of Route 28, 1,300 feet north of the Massachusetts boundary (Fig. 6, locality 2). Several specimens immediately suggested calamites. The largest was 2 feet long, 6 inches wide. But the structure is inorganic; foliation, intersecting a slightly folded quartz vein, produces a ribbing suggestive of Calamites.

Possible extension of Worcester phyllite into New Hampshire. The large body shown as Worcester phyllite north of Worcester (Fig. 8) splits into two branches toward the north. One of these, with an increase in the grade of metamorphism, extends northeastward as far as Lowell (Fig. 8, locality 3). Since this branch does not extend into New Hampshire, it need not concern us further. The other branch extends north to the state boundary. On the geological map of New Hampshire the continuation of this belt is shown as a phyllite member of the Merrimack group (*SOmp*). But if Emerson's age determinations and correlations in Massachusetts are correct, it is Worcester phyllite of Pennsylvanian age. If so, the present writer would suggest that the phyllite rests unconformably on the Merrimack group and is downfolded in a small syncline.

Relation to alkaline rocks in Southern Maine. The relations of the Mt. Agamenticus complex to the Merrimack group in southern Maine is pertinent (Wandke, 1922). This complex contains typical alkaline rocks, including biotite granite, alkaline granite, and alkaline syenite. Microperthite, arfvedsonite, riebeckite, aegerite, and fayalite are characteristic. As will be shown

later, these alkaline rocks are Mississippian (?). The Mt. Agamenticus complex cuts the Kittery quartzite. Moreover, the undeformed and unmetamorphosed character of the rocks comprising the complex shows that it is younger than the folding and metamorphism of the entire Merrimack group. Hence the Kittery, Eliot, and Berwick are older than the Mississippian (?) and older than the orogeny, which is probably Middle Devonian.

Relation to the Waterville slates. The lithology of the Eliot and Berwick formations suggests that they may be correlated with the Vassalboro and Waterville formations near Waterville, Maine (Fig. 8, locality 1). The Waterville slate contains *Monograptus colbiensis*, indicating a Clinton (Middle Silurian) age (Perkins and Smith, 1925).

The Waterville slate is composed of calcareous shales, arenaceous shales, and slate with interbedded quartzite. The Vassalboro, which underlies the Waterville, contains quartzite, mica schist, phyllite and calcareous phyllite (Fisher, 1941, p. 124). Where more highly metamorphosed the Vassalboro is called the Androscoggin formation. The total thickness of the Vassalboro and Waterville formations is given by Fisher (1941) as 6,500 feet.

Perkins and Smith (1925, p. 223) conclude that, inasmuch as the Vassalboro is transitional upward into the Waterville slate, both formations are Middle Silurian. Southwesterly along the strike these formations become progressively more metamorphosed; such rocks as biotite-garnet gneiss, marble, and lime-silicate gneisses are common. The various formations names used by Fisher (1941) in the different metamorphic zones need not concern us here. The Eliot and Berwick, where least metamorphosed, consist of slate, calcareous slate, and dark phyllite. The total thickness of the Eliot and Berwick formations is given by Freedman (1950) as 13,500 feet. Where more metamorphosed, garnet and lime-silicates appear.

A correlation of the Eliot and Berwick formations with the Vassalboro (Androscoggin) and Waterville seems reasonable. Only a general correlation is implied and not that the Vassalboro is the exact equivalent of the Eliot, nor that the Berwick is the exact equivalent of the Waterville.

Unfortunately the stratigraphic units have not been traced all the way from Waterville to New Hampshire. Fisher traced the formations for nearly 60 miles southwest from Waterville to latitude 43° 50′ (Fig. 8). Southwest of here is a gap of ten miles for which no maps have been published. Katz's mapping covers that part of Maine southwest of latitude 43° 45′. Unfortunately Katz's mapping is not too useful, because, under the influence of Keith, he was obsessed with the idea that the grade of metamorphism was a function of age.

The way in which the formations may connect across the unmapped area is shown in Fig. 8 by broken lines. The Pejepscot formation of Fisher may be metamorphosed Kittery..

In conclusion, chiefly on the basis of lithologic similarity, but also because of presumed continuity along the strike, the Merrimack group of New Hampshire is tentatively correlated with the Waterville and Vassalboro formations, and thus assigned to the Middle Silurian.

Relation of the Fitch formation. The Littleton formation extends northeasterly across central New Hampshire. The Merrimack group underlies the Littleton formation (Freedman, 1950) and thus occupies the same stratigraphic position as the Fitch formation of western New Hampshire. Moreover, the Merrimack and Fitch formations are rather similar lithologically. The same lithologic types are present, but it is true that the Fitch has a somewhat higher percentage of marble. Moreover, the Merrimack is much thicker. These facts suggest that the Merrimack is an easterly, more clastic facies of the Fitch.

The Clough and Kittery are both quartzites and may be the same age. But the Clough is much thinner and purer than the Kittery. The Rye formation, consisting of metamorphosed argillaceous sediments and volcanics, suggests the Ammonoosuc and Partridge formations. Thus the sequence in southeastern New Hampshire duplicates in its broader features that in western New Hampshire.

Summary. Several lines of evidence suggest that the Merrimack group is Middle Silurian. It is older than the supposedly Pennsylvanian Worcester phyllite and the Mississippian (?) Agamenticus complex. Lithologic similarity and presumed continuity along the strike suggests that it can be correlated with the Middle Silurian Waterville and Vassalboro formations of Maine. Moreover, the lithology and structural position indicate that the Merrimack can be correlated with the Middle Silurian Fitch formation of western New Hampshire. The Rye formation

may be the stratigraphic equivalent of the Ordovician (?) Ammonoosuc and Partridge formations.

If the Waterville formation can be traced southwesterly from Waterville to southeastern New Hampshire, the proposed correlation of the Merrimack group would be proved. But until this is done, it is advisable to place a query on the age assigned to this group.

Mississippian (?)

The Moat volcanics, which are the extrusive phase of the White Mountain series, rest unconformably on the Littleton formation, and hence are Devonian or younger. Enough time must have elapsed between the deposition of the Littleton and the eruption of the Moat volcanics for folding, metamorphism, intrusion of the Oliverian and New Hampshire plutonic series, and deep erosion. It seems unlikely that the Moat could be older than Mississippian. On lithologic grounds the plutonic rocks of the White Mountain series are part of the alkaline rocks of New England and can thus be correlated with the Quincy granite in eastern Massachusetts. The Quincy granite is older than the Pennsylvanian rocks of the Norfolk Basin (Emerson, 1917, p. 188), because Pennsylvanian fossils have been described from locality 9, Fig. 8 (Grabau et al, 1898), and Allegheny fossils have been described from locality 11, Fig. 8 (Knox, 1944). The alkalic rocks are tentatively assigned to the Mississippian.

A few other fossiliferous localities in eastern Massachusetts may be mentioned here because of the bearing they may have on the interpretation of the stratigraphy of New Hampshire. Fossiliferous Lower Cambrian and Middle Cambrian rocks are found around Boston (Fig. 8, localities 7 and 8; Emerson, 1917, p. 35-39). Foerste has described a Middle Silurian fossil that is said to have come from near Topsfield, Massachusetts (Fig 8, locality 5). The Newbury volcanics (Fig. 8, locality 6) are probably Upper Silurian or Lower Devonian (Emerson, 1917, p. 163-164).

Plutonic Rocks

Newburyport Quartz Diorite

Emerson (1917, p. 172-181) assigned the Newburyport quartz diorite to a group called "Dedham granodiorite and associated rocks." Although this group was first considered Silurian or Devonian (Emerson, 1917, p. 164), La Forge (1932, p. 21-22) later concluded that it was pre-Devonian. Billings (1929) and Dowse (1950) have shown that at Hoppin Hill, near North Attleboro, Massachusetts (Fig. 8, locality 10) the fossiliferous Lower Cambrian rests unconformably upon the Dedham granodiorite. Assuming that all the correlations have been correctly made, the Newburyport quartz diorite is thus pre-Cambrian.

Serpentine

The serpentine body in the northernmost part of New Hampshire is presumably younger than the surrounding rocks of Ordovician (?) age. The ultramafic rocks of Vermont, most of which are serpentinized, are intruded into rocks that probably range in age from Cambrian to Lower or Middle Ordovician (Chidester *et al.*, 1951, p. 4). Moreover, there are no authentic examples in New England of ultramafic rocks cutting demonstrable Silurian or Devonian rocks. Consequently, the ultramafic rocks have been generally considered to be Late Ordovician. Other geologists, however, believe that the ultramafic rocks may be as young as Devonian (Dresser and Denis, 1944, p. 416).

Highlandcroft, Oliverian, New Hampshire, and White Mountain Series

Stratigraphic Methods. The Highlandcroft plutonic series is unconformable beneath the Silurian, but cuts rocks that are almost certainly Ordovician. It has been considered to be Late Ordovician (Billings, 1937, p. 500).

The Silurian Clough quartzite is locally metasomatized near the Oliverian plutonic series (Billings, 1937, p. 502), which is therefore younger than the Silurian. Because of its structural relations it has generally been considered to be younger than the Lower Devonian Littleton formation, but older than the final stages of the orogeny.

The New Hampshire plutonic series is younger than the Littleton formation but older than the Moat volcanics. Hence, it has been considered to be Middle or Late Devonian, probably the latter.

The White Mountain plutonic-volcanic series, for reasons given above in the discussion of the age of the Moat volcanics, is considered to be Mississippian (?).

Radioactive ages. Recently a systematic effort has been made by J. B. Lyons and his associates to date the different

plutonic series of New Hampshire by a radioactive method devised by E. S. Larsen, Jr. Unweighted averages (Faul, 1954, p. 267-268) suggest the following ages in millions of years: Highlandcroft, 424; Oliverian, 322; New Hampshire, 321; and White Mountain, 235. More complete data (J. B. Lyons, D. Gottfried, W. L. Smith, H. W. Jaffe, and C. E. Waring, U. S. Geological Survey, report in preparation) indicate the following ages in millions of years: Highlandcroft, 388 ± 33; Oliverian, 317 ± 22; New Hampshire, 319 ± 34; and White Mountain, 233 ± 18. Using the most recent table by Holmes (1947) this would mean that the Highlandcroft is earliest Late Ordovician, the New Hampshire and Oliverian are earliest Devonian, and that the White Mountain is Mississippian. It should, of course, be realized that Holmes's time scale for the Paleozoic is exceedingly tenuous. Moreover, the Larsen method may not be accurate to within better than 10%. Nevertheless, it is gratifying to see that the radioactive and stratigraphic method agree relatively well.

The radioactive method suggests that the Oliverian and New Hampshire series are essentially the same age, are one consanguineous series, and earliest Devonian. But, since it is clear in the field that the New Hampshire series is younger than Lower Devonian, there appears to be some minor error either in Holmes's table or Larsen's method. It may well be that the New Hampshire series is Middle Devonian and not Upper Devonian, as indicated with a query on the geological map.

The age of the Highlandcroft series is somewhat too great for the tentative correlations that are given in the explanation on the geological map. Again, this may be an error in the radioactive method, but in this case it is equally possible that the Albee, Ammonoosuc, and Partridge formations are Middle Ordovician rather than Upper Ordovician as suggested on the geological map.

The age of the White Mountain series by radioactive methods agrees with that obtained by stratigraphic methods.

In summary, the radioactive ages are, in general, in agreement with the stratigraphic ages, except that they suggest that the New Hampshire series may be Middle rather than Upper Devonian, and that the Highlandcroft may be earliest Late Ordovician, thus making the Albee, Ammonoosuc, and Partridge formations Middle Ordovician or older.

GEOLOGICAL STRUCTURE

General Statement

The major structural trend in New Hampshire is north-northeasterly, in harmony with the general trend of the whole Appalachian system. In the southwestern part of the state the trend is northerly, in the central part it is northeasterly. These trends result from major anticlinoria and synclinoria, the names of which are given on the structure map in the lower left-hand corner of the sheet containing the geological map. The Bronson Hill anticline lies in the western part of the state, the Rockingham anticlinorium in the southeastern part, and the Merrimack synclinorium lies between. The Coös anticlinorium is in the northern part of the state. Faults, generally following the trends of the major folds, are also important; some are thrusts, others are normal faults. The older plutonic series, especially the Oliverian and New Hampshire series, also participate in this northeasterly trend; this is strikingly shown by the domes of the Oliverian plutonic series and such bodies as the Mt. Clough, Cardigan, and Fitchburg plutons. The Winnipesaukee pluton is exceptional in that it is nearly circular. The White Mountain plutonic-volcanic series, contrasting sharply with the older rocks, is concentrated in a belt that trends N. 10° W. across the older structures.

Minor structural features, such as minor folds, foliation, lineation, and joints are conspicuous in the field. Unfortunately, in a general survey of the structure, such as that presented here, a detailed consideration of these features is impossible.

The major orogeny in New Hampshire is Acadian (Middle and Late Devonian) in age. It was at this time that the major folding, thrust faulting, regional metamorphism, and emplacement of the Oliverian and New Hampshire plutonic series occurred. Exactly when this orogeny took place cannot be stated, but it is probably Middle and/or Late Devonian. There is evidence that the Taconic revolution affected western New Hampshire and was accompanied by the intrusion of minor bodies of plutonic rock. The volcanism and intrusion of the White Mountain series is probably Mississippian. Some of the normal faulting in the southwestern part of the state is Triassic. There is no evidence that the Late Paleozoic Appalachian revolution played a significant role in New Hampshire.

Folds

General statement. Inasmuch as the structure is dominated by the major folds, it is appropriate that they should be described first. Although a geographic order, such as from northwest to southeast, might seem logical, a more effective approach is to describe the Bronson Hill anticline first, then the structural features to the northwest of it, followed by a discussion of the Rockingham anticlinorium, and finally the Merrimack synclinorium.

Bronson Hill anticline. The Bronson Hill anticline which, because of its complexity, might more appropriately be called an anticlinorium, was named from Bronson Hill, a relatively minor topographic feature 5 miles south-southwest of Franconia. This anticline is labelled on the structure map. It is conspicuous on the geological map from the Maine border, 10 miles northeast of Berlin, to the Massachusetts border in the extreme southwest corner of the state. Throughout most of its extent the core of the anticline is composed of Ammonoosuc volcanics and the plutonic rocks of the Oliverian series. The length in New Hampshire is 150 miles; the width, as defined for this paper, is 6 to 16 miles.

Although the core is composed of Ammonoosuc volcanics and rocks of the Oliverian series, both flanks show the Clough, Fitch, and Littleton formations. The Bethlehem gneiss, although plutonic, is also symmetrically disposed about the anticlinal axis. The symmetry, although complicated in detail, is well shown between Franconia and Moose Mountain, 8 miles northeast of Hanover. The Clough, Fitch, and Littleton on the northwest limb can be followed throughout this distance with only minor interruptions. For considerable distances the Bethlehem gneiss is inserted in the lower part of the Littleton formation. The Clough and Fitch on the southeast limb are not so continuously exposed, but they are present for several miles southwest of Warren. The Bethlehem gneiss appears further east, and the Littleton formation lies still further east.

On the west limb of the Bronson Hill anticline south of Moose Mountain the sequence of Ammonoosuc, Clough, Fitch and Littleton can be followed to Perry Mountain, 5 miles northeast of Charlestown. East of Perry Mountain the sequence of Clough, Fitch and Littleton is exposed on the east limb.

Around Acworth there is an axis depression in the Bronson

Hill anticline, so that for 4 miles the Littleton formation extends from west to east across the axis of the anticline.

South of Acworth the east limb is fairly straight, showing a sequence of the Ammonoosuc, Partridge, Clough, and Littleton formations. The west limb can be followed to the extreme southwest corner of the state, but a major axis depression near Chesterfield greatly complicates the map pattern.

Northeast of Franconia the core of the Bronson Hill anticline is occupied chiefly by the plutonic rocks of the Oliverian series, with lesser amounts of the Ammonoosuc volcanics. West of Franconia the Garnet Hill syncline, the axial trace of which is 1 mile northwest of Sugar Hill, is a subsidiary fold on the northwest flank of the Bronson Hill anticline (section CC′). The structure of the rocks of the Oliverian series within the Bronson Hill anticline will be discussed further in a later section that deals with the plutonic rocks. The Bronson Hill anticline is shown and labelled on all the structure sections accompanying the geological map except AA′, which is too far north.

Salmon Hole Brook Syncline. The Salmon Hole Brook syncline lies northwest of the Bronson Hill anticline, from which it is separated by the Northey Hill thrust, described on a later page. The Salmon Hole Brook syncline is separated from the Coös ancliclinorium on the northwest by the Ammonoosuc thrust, described in a later section. The name of this syncline comes from the stream that flows westerly from Sugar Hill to the Ammonoosuc River.

The axial trace of the Salmon Hole Brook syncline can be followed in a southwesterly direction from 3 miles northwest of Franconia. For 16 miles, that is, as far as Pike, the axial trace is very close to the Northey Hill thrust. Thus, between the Gale River and Pike, the Salmon Hole Brook syncline is only the western limb of a syncline composed of all the stratigraphic units from the Albee formation to the Littleton formation. In much of this area, although the map pattern is that of a syncline plunging northeast, the minor folds actually plunge southwest. This is interpreted to mean that the plunge of the syncline is here inverted. South of Pike, the axial trace lies about 1 mile west of the Northey Hill fault and passes through Orfordville. Still further south, the axial trace passes west of the Lebanon granite, whence it continues southward for 25 miles more to the Connecticut

River. Whereas the Orfordville formation occupies the center of the syncline at Orfordville, further north successively younger formations form the center of the syncline.

In the vicinity of Hanover and further south, several additional folds lie east of the Salmon Hole Brook syncline, but west of the Northey Hill fault. These folds have been recently described by Lyons (1955). One is the Lebanon dome, the core of which is occupied by the Lebanon granite. Although this fold plunges north at its northern end, in accordance with the regional map pattern, the south end also plunges north. That is, the plunge is here inverted. Southeast of the Lebanon dome a syncline is indicated by the pattern of the base of the Post Pond volcanics 1½ miles east of Lebanon, and by two bands of Hardy Hill quartzite north of the Mascoma River. The pattern is that of a syncline plunging south; the minor folds actually plunge steeply north, so that here, as at the southern end of the Lebanon dome, the plunges are inverted. Toward the southwest this syncline passes through the quartz diorite and merges with the main Salmon Hole Brook syncline.

An anticline lies 1 mile west of Meriden. This is shown by the pattern of the Hardy Hill quartzite and the base of the Post Pond volcanics. Still further east a narrow syncline is indicated by the long tongue of Post Pond volcanics that extends south through Cornish and South Cornish almost to Charlestown.

Coös Anticlinorium. The Coös Anticlinorium occupies all of northern New Hampshire northwest of the Ammonoosuc thrust and north of Woodsville. The name is from Coös County, the most northerly county in New Hampshire. In northernmost New Hampshire the principal fold within this anticlinorium is the Pittsburg anticline, the crest of which is occupied by the large oval area of Waits River limestone extending for 16 miles south-southwest from Pittsburg. Near Pittsburg the anticline plunges north, whereas at the southwest end it presumably plunges south. All of northern New Hampshire east of this anticline forms the east limb of the Coös anticlinorium. The western limb lies west of the Pittsburg anticline.

In west-central New Hampshire several minor folds are present. One of these is the Walker Mountain syncline, the axial trace of which lies directly northwest of the Ammonoosuc thrust. The name comes from Walker Mountain, 3 miles west-southwest of Littleton. The fossiliferous Silurian and Devonian formations are preserved in the synclinal trough. The axial trace may be followed southwest through Woodsville. Moreover, 2 miles northwest of Piermont, the base of the Albee formation crosses from New Hampshire into Vermont, but turns back toward the north immediately west of the Connecticut River (White and Billings, 1951). North of Littleton the Devonian rocks on Dalton Mountain are in the synclinal trough. Still further northeast the Walker Mountain syncline cannot be recognized.

The Albee formation on Gardner Mountain forms the core of the Gardner Mountain anticline, which crosses the Connecticut River into Vermont both northeasterly and southwesterly, but loses its identity in both directions. The Ammonoosuc volcanics northwest of Gardner Mountain lie in the trough of the Monroe syncline.

Rockingham Anticlinorium. The Rockingham anticlinorium, named from Rockingham County, lies in southeastern New Hampshire, between the Atlantic Ocean and the Fitchburg pluton. The anticlinorium trends northeasterly; the major folds within the anticlinorium are, from southeast to northwest, the Rye anticline, the Great Bay (Eliot) syncline, and the Exeter anticline (largely occupied by the Exeter pluton).

The Rye anticline, named from the township of Rye, extends in a southwesterly direction from 1 mile south of New Castle for at least 12 miles to Hampton Falls. The Rye formation occupies the core of the anticline. The patterns shown by the top and bottom of the metavolcanic member of the Rye formation, as well as the pattern shown by the top of the Kittery quartzite, indicate an anticline that plunges southwesterly; the minor folds observed in the field are consistent with such an interpretation (Billings and Heald, reconnaissance, 1951).

The axial trace of the Great Bay (Eliot) syncline passes near Newington, Stratham, and 2 miles east of Exeter. The trough of the syncline is occupied by the Eliot formation. Possibly the band of phyllite that passes through Newton may be in the trough of the southwesterly continuation of this syncline.

The Kittery quartzite is discontinuously exposed around the Exeter diorite, suggesting that this pluton occupies the core of a fold. This fold, like the Rye anticline, appears to plunge southwest at its southwest end.

The rocks between the Exeter and Fitchburg plutons strike northeast and dip steeply; because they lie on the northwest flank

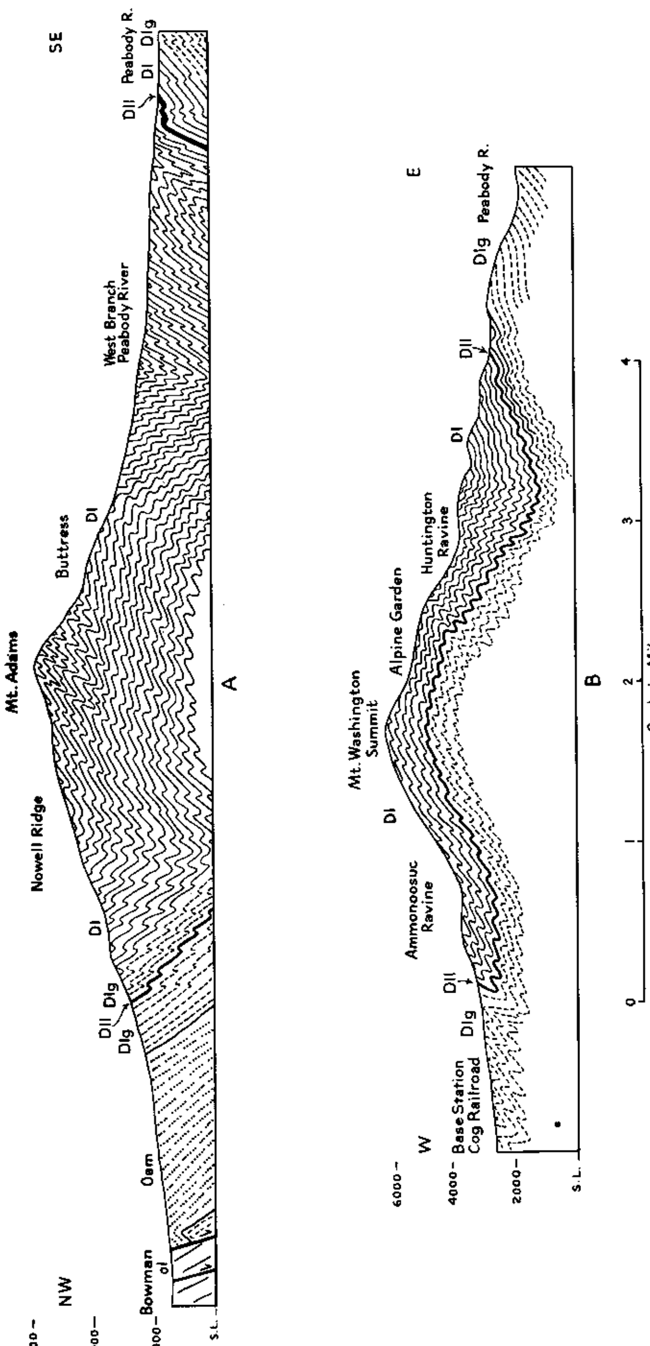

Figure 9. Structure sections across the Presidential Range. Ordovician (?): *Oam* = Ammonoosuc volcanics. Lower Devonian: *Dlg* = gneiss of Littleton formation, *Dll* = lime silicate member (Boott member) of Littleton formation, *Dl* = interbedded schists and quartzites of Littleton formation. Middle or Upper Devonian (?): *ol* = Oliverian plutonic series. A. Section across Mt. Adams. B. Section across Mt. Washington to show minor anticline within main syncline.

of the Exeter anticline they become progressively younger to the northwest. Most of the rocks shown on the geological map as undifferentiated Merrimack group, at least that part lying northwest of a line passing through Kingston, Atkinson and Salem, lie on the northwest limb of an anticlinorium (A. Sriramadas, 1955).

Merrimack Synclinorium. East of the Bronson Hill anticline and northwest of the Rockingham anticlinorium is a large area of Littleton formation, all in the sillimanite zone of metamorphism. Inasmuch as this band of the Littleton formation is bordered on either side by older strata, it must occupy a synclinorium. This structural feature is called the Merrimack synclinorium, because much of it is drained by the Merrimack River and its tributaries. Fig. 9, 10, and 11 contain some additional structure sections to supplement the sections accompanying the geological map.

Fig. 9A illustrates the structure of the Presidential Range. Above the plutonic rocks of the Oliverian series are the Ammonoosuc volcanics, which are overlain successively by three units of the Littleton formation, the lower gneiss, the intermediate Boott member (lime-silicate rocks), and the upper interbedded sillimanite schists and quartzites. These three members of the Littleton formation reappear on the southeast side of the range, where they dip northwesterly. The Presidential Range is thus a syncline. Mt. Washington is underlain by an anticline within this major syncline (Fig. 9B).

Throughout much of western New Hampshire the western limb of the Merrimack synclinorium is invaded by large bodies of the New Hampshire plutonic series. These relations are well shown on section DD′, EE′, and FF′ accompanying the geological map. A structure section across Mt. Monadnock is given in Figure 10. The mountain is held up by the resistant quartzites and sillimanite schists in the center of a syncline.

The geological structure in the center of the Merrimack synclinorium is shown in Fig. 11 by a series of structure sections in the Plymouth quadrangle (Moke, 1946). Because of the lack of good horizon markers in the Littleton formation, the folds are necessarily diagrammatic. The sections also show that the metamorphic rocks are invaded by plutonic rocks of the New Hampshire and White Mountain series.

Thrust Faults

General statement. Three major thrust faults are shown in western New Hampshire on the structure map. They are, from northwest to southeast, the Monroe, Ammonoosuc and Northey Hill. Several additional minor thrusts are also shown on the geological map; space will not permit discussion of these. The Seabrook thrust, in the extreme southeastern corner of New Hampshire, will be discussed briefly.

Ammonoosuc Thrust. The Ammoonoosuc thrust extends from the west side of the Pilot Range in a southwesterly direction to Woodsville, south of which the thrust is very close to the Connecticut River. Sixteen miles south of Hanover the Ammonoosuc thrust crosses the Connecticut River into Vermont and does not reappear further southwest in New Hampshire. The known length of the Ammonoosuc thrust in New Hampshire is thus 85 miles. It is possible that it reappears east of the Pliny-Pilot complex and continues to and beyond the Maine border.

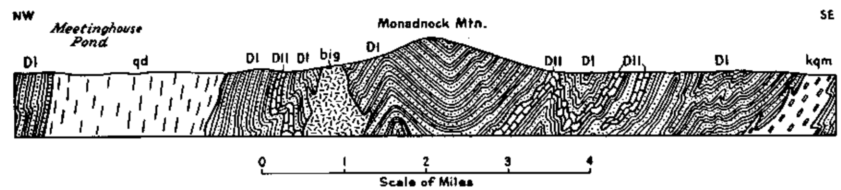

Figure 10. Structure section across Mt. Monadnock. Lower Devonian: *Dl* = Littleton formation; *Dll* = lime-silicate member of Littleton formation. Upper Devonian (?) New Hampshire plutonic series: *qd* = quartz diorite (Spaulding quartz diorite); *kqm* = Kinsman quartz monzonite; *big* = binary granite (Concord granite). After K. Fowler-Billings.

This fault is named from the Ammonoosuc River, northwest of which, between Littleton and Bath, it is typically exposed (Billings, 1937, p. 525-530). The fault was first recognized here because of a pronounced stratigraphic hiatus. Strata high up in the Littleton formation are in contact with the Ammonoosuc volcanics and even with the Albee formation. Seven thousand feet of strata are missing at the fault. Silicified zones along the thrust in this area consist of a chert-like rock composed of fine-grained quartz. Relatively long compared to their width, the silicified zones are only a few feet thick in places, but elsewhere they are several scores of feet thick. Mylonites along the thrust have been described (Billings, 1936, p. 527-528).

South of Woodsville there is little stratigraphic evidence for the fault. Between Woodsville and Piermont the rocks on either side of the fault belong to the Albee formation. Between Piermont and a point on the Connecticut River 8 miles south of Hanover, the rocks on either side of the fault belong to the Orfordville formation, but, in the area around Plainfield, Lyons (1955, p. 133) has described stratigraphic discontinuities along the fault.

The attitude of the fault is known because it is exposed in several places. Between Littleton and Woodsville the northwesterly dip at five localities is 50°, 32°, 32°, 36°, and 39°; the average is 38° N.W. Lyons (1955, p. 133) says that in the Hanover area the dip ranges from 33° to 50° W. The Ammonoosuc thrust is younger than the regional metamorphism, because there is a sharp discontinuity in the grade of metamorphism along the fault.

Northey Hill Thrust. The Northey Hill thrust is shown on the geological map as extending in a south-southwesterly direction from 2 miles west-northwest of Bethlehem to South Charlestown on the Connecticut River, a distance of 86 miles. The fault reappears at two places further southwest in New Hampshire along the Connecticut River, 3 miles southwest of Westmoreland and 8 miles south-southwest of Westmoreland. The minimum length of the thrust would thus be 110 miles.

The type locality is Northey Hill, 4 miles west of Franconia. Here the chief evidence for the fault is the discontinuity of structures. This is shown in the geological map, and more strikingly, on the geological map of the Moosilauke quadrangle (Billings, 1937). Although for several miles northeast and southeast of Northey Hill the Littleton formation on the northwest side of the fault is in contact with several different formations on the southeast side of the fault, still further southwest the Littleton formation is on either side of the fault. But the fault can be readily followed for several more miles as far as the latitude of Landaff because of the presence of exotic blocks of Clough quartzite and Ammonoosuc volcanics in the midst of the Littleton formation. Southwest of Northey Hill the fault strikes N. 60° E., but northeast of Northey Hill the trace of the fault drifts 2,000 feet northwest of the projected strike in dropping 600 feet. This implies that the dip here is about 17° NW. Further southwest in New Hampshire the dip is apparently steep, because the trace of the fault crosses hills and valleys without much change in the trend of the trace of the fault.

For 10 miles south of Landaff, the northwest border of a body of Bethlehem gneiss coincides with the Northey Hill thrust. But in the vicinity of Pike there is stratigraphic evidence of the fault, because the Orfordville formation is here in contact with the Littleton formation; the stratigraphic hiatus here is at least 12,000 feet. For 80 miles to the southwest the same general relations hold, but the fault is very difficult to locate precisely because schists of the Orfordville formation are in contact with schists of the Littleton formation.

The steep dip that characterizes the Northey Hill thrust throughout so much of its extent is believed to be due to later deformation. The Northey Hill thrust, unlike the Ammonoosuc thrust, is nowhere silicified. Moreover, there is no break in the grade of metamorphism across the fault. It is thus older than the regional metamorphism.

Monroe Thrust. The Monroe thrust is shown in only two places on the geological map. One locality is along the Connecticut River north of Monroe, where the fault extends across New Hampshire for 5 miles. A small segment, 2 miles long, is shown near North Stratford. The fault is believed to extend from North Stratford across Vermont through Monroe, New Hampshire, to a point 2 miles southwest of West Lebanon (Lyons, 1955, p. 133-134). The total length is thus about 85 miles. The evidence for the fault is primarily stratigraphic. North of Monroe, the Gile Mountain formation is in contact with the Ammonoosuc volcanics. Thus, there is a stratigraphic hiatus of at least 10,000 feet. The dip here is 65° NW. (Eric, White, and Hadley, 1941). In Vermont, 12 miles north-northwest of Littleton, northwesterly trending beds on the southeast side of the fault strike into northeasterly trending strata on the northwest side (Eric, 1942). Four miles west of Woodsville the biotite isograd is offset slightly by the fault (White and Billings, 1951, p. 670). Although the dip north of Monroe is northwest, throughout most of its extent the average dip of the fault is vertical and in places it dips southeast. Thus, although it is mostly older than the regional metamorphism, the last movements are believed to have been later than the regional metamorphism and the fault was deformed to its present steep dip. The evidence for the fault at North Stratford is very tenuous. Reconnaissance mapping indicates that the Orfordville is absent here, but north of the Goback-Gore Mountain stock of Conway granite the Orfordville is present; the fault is apparently absent, but detailed mapping is necessary here.

Seabrook Thrust. This fault lies in the extreme southeast corner of the state and is 4 miles long. If the Newburyport quartz diorite is pre-Cambrian, a stratigraphic hiatus exists between it and the Eliot formation to the north because all the Rye formation is missing. This necessitates a fault. As indicated in the descriptive section, the northern part of the area mapped as Newburyport is a plutonic breccia of Newburyport quartz diorite cemented by binary granite. This suggests a fault breccia that has been intruded by granite.

Normal Faults

General Statement. Most of the known normal faults are confined to a belt 12 miles wide in the extreme western part of the state, between Enfield and the Massachusetts border, a distance of 65 miles. Only those more than 10 miles long will be considered here.

Triassic border fault. In the extreme southwest corner of the state a fault bounds the Kinsman quartz monzonite on the southeast. This fault is called the Triassic border fault in section FF′ because further south in Massachusetts it borders the Triassic rocks on the east (Emerson, 1917). The truncation of the structures along this fault is readily apparent on the geological map. The dip cannot be determined in New Hampshire, but in Massachusetts, 10 miles south of the state line, the fault dips 60° W. in one exposure and 35° NW in the other (Keeler and Brainard, 1940). In southwestern New Hampshire the block on the northwest side has been downdropped 15,000 to 20,000 feet.

Mine Ledge fault. The south end of a north-south fault lies 4 miles northwest of Keene. This fault is about 12 miles long. The south end of this fault is a silicified zone more than a mile long and several hundred feet wide (Moore, 1949, p. 1658). The dip of the fault ranges from 70° W. to vertical; the stratigraphic throw is 3,000 to 4,000 feet, with the downthrow on the west.

Graben west of Keene. The Mine Ledge fault forms the eastern border of a graben. The western border fault is ½ mile to the west. This fault dips 55° E. Gouge as much as 25 feet thick is present, and the block on the east is downthrown 3,000 feet.

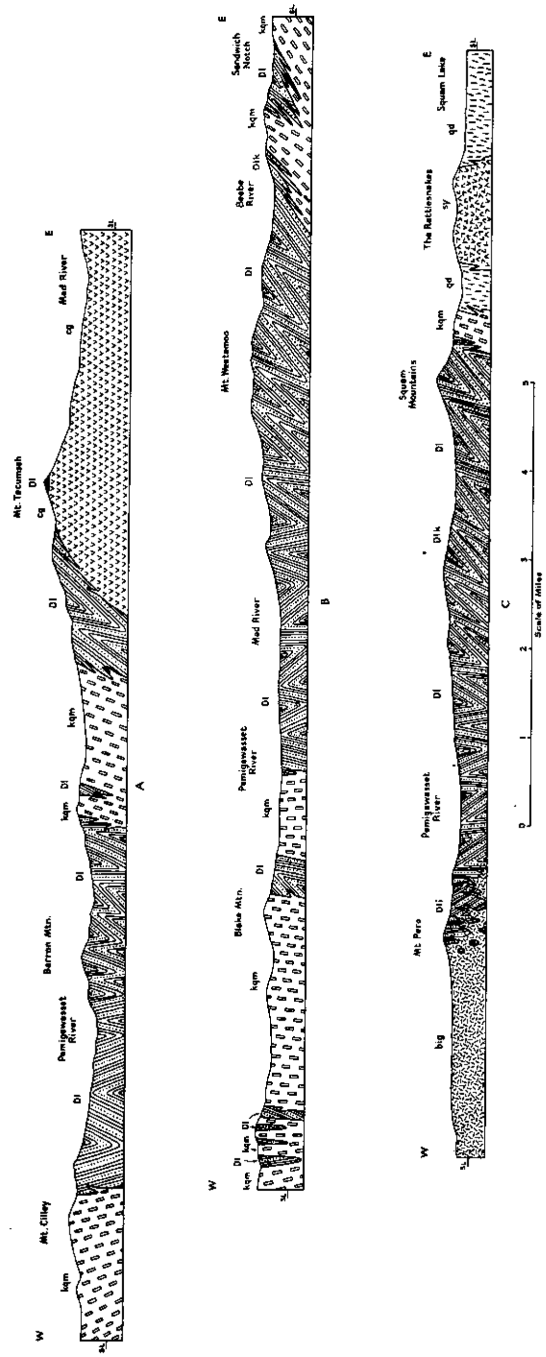

Figure 11. Structure sections across the Plymouth quadrangle. Lower Devonian: *Dl* = Littleton formation; *Dli* = Littleton formation injected by dikes and sills of binary granite; *Dlk* = Littleton formation injected by dikes and sills of Kinsman quartz monzonite. Upper Devonian (?) New Hampshire plutonic series: *qd* = quartz diorite (Winnipesaukee quartz diorite); *kqm* = Kinsman quartz monzonite; *big* = binary granite (Concord granite). Mississippian (?) White Mountain plutonic-volcanic series: *sy* = syenite; *cg* = Conway granite. After C. B. Moke.

There are two other graben in this area — one at Hyland Hill and the other at West Hill.

Grantham fault. This large fault extends from Enfield on the north end of Mascoma Lake to 2 miles north of Acworth, a distance of 28 miles. The dip is 65° to 70° E., the downthrown side is on the east, and the stratigraphic throw is 4,000 feet (C. A. Chapman, 1939, p. 165). Silicified zones, locally present along the fault, are several hundred yards long and up to 200 feet wide.

Fault northeast of Canaan Center. A fault that trends N. 75° W. 2 miles northeast of Canaan Center is conspicuous on the geological map. The fault has not been observed, but the distribution of outcrops of the Ammonoosuc volcanics, the plutonic rocks of the Oliverian series, and the Bethlehem gneiss indicates that the south side is downthrown.

Pine Peak fault. The Pine Peak fault, northwest of the Presidential Range, extends for 14 miles in a northeasterly direction from near Fabyan to north of Randolph. The fault is marked by numerous silicified zones. Although the southeast side is downthrown and the relation of the trace of the fault to topography indicates a steep dip, the direction of dip is unknown (Billings, 1941, p. 915).

Flint Hill fault. In the southeastern part of the state a silicified zone can be traced in a northeasterly direction for 17 miles from Raymond almost to the Isinglass River (Freedman, 1950, p. 479). This fault is apparently very steep, and the northwest side is probably downthrown.

Silicified Zones. A number of silicified zones are shown on the geological map. These are lines along which occasional bands of silicified rock are found. Three are shown about 14 miles west-northwest of Portsmouth. Two long silicified zones lie 3 and 7 miles, respectively, northwest of Manchester. Three others are 14 to 20 miles west-northwest of Nashua. Another is 6 miles north of the northwest end of Lake Winnipesaukee. Some are also shown near Berlin.

These silicified zones are probably all along faults, but inasmuch as no direct evidence of faulting was obtained, they have been separately designated on the map, but readers interested in silicified zones should clearly understand that many of the normal

faults and at least one of the thrust faults (Ammonoosuc thrust) are characterized by silicified zones as numerous as those in the silicified zones as shown on the geological map.

Plutonic Rocks

General Statement

The study of the structure of the plutonic rocks is concerned with the shape of the individual bodies, the planar and linear features found within these bodies, and the mechanism by which the rocks were emplaced. One of the important results of the study of the geology of New Hampshire in the last 25 years has been to show that the various plutonic series of the state are not all structurally alike (Billings, 1945). The Highlandcroft series is not widely distributed. The Oliverian series and the earlier members of the New Hampshire series show many features in common. They are large concordant sheets and lenses lying in the metamorphosed older rocks and, in many instances, were involved in at least some of the deformation. The plutonic rocks of southeastern New Hampshire have not been intensely studied but, like the Oliverian and New Hampshire series, many of them are also large sheets, or lenses. Finally, the White Mountain series, structurally very different from the older series, is characterized by discordant ring-dikes, stocks, and a batholith.

The present section of this report is concerned not only with the shapes of these bodies of plutonic rocks, but also an explanation of these shapes.

Highlandcroft Plutonic Series

There are only five bodies of the Late Ordovician (?) Highlandcroft series in west-central New Hampshire. One of these, 2 miles west of Littleton, is a small slice along the Ammonoosuc thrust. Much of this rock, originally quartz monzonite, is mylonitized and near the main thrust plane is converted to mylonite schist. The body near Piermont is a large vertical sheet composed of coarse-grained quartz monzonite, that has a weak to moderate foliation; the rock is highly schistose at the contacts (Hadley, 1942, p. 136). Much of the present shape of the body is probably the result of the Devonian deformation. In the small body, 6 miles west-northwest of Littleton, the Highlandcroft has also been reduced to mylonite schist (Billings, 1937, p. 500). The two largest bodies, one 2 miles northwest of Littleton and the other around Lancaster, appear to be irregular bodies; much of the rock is massive, but some of it has been reduced to mylonite schist. The body around Lancaster — mostly diorite and quartz diorite — characteristically contains inclusions of the Albee formation, four of which are large enough to show on the geological map. Apparently the Albee formation was fractured by uprising magma, and many tongues penetrated the broken rock to form a large-scale plutonic breccia.

Oliverian Plutonic Series

The Oliverian plutonic series is largely confined to the Bronson Hill anticline, the main features of which have been described on earlier pages. The Bronson Hill anticline is not a single fold with a single axis. Instead it consists of a series of domes, the cores of which are composed of the Oliverian plutonic series. These domes are named on the structure map. From northeast to southwest they are: (1) Jefferson, (2) Owls Head, (3) Smarts Mountain, (4) Mascoma, (5) Croydon, (6) Unity, (7) Alstead (which extends from South Acworth to southwest of Gilsum — the structure map does not make this clear), (8) Swanzey-Westmoreland-Surry, (9) Vernon, and (10) the north end of one, south of Winchester, that is not named on the structure map. Between the Vernon and the Swanzey domes there is a large structural basin occupied by the Kinsman quartz monzonite.

An *en echelon* pattern of the domes is conspicuous in the west-central part of the state, where the axes of the domes trend north-south, slightly diagonal to the trend of the whole anticline. In the axes depressions between the domes, rocks as young as the Clough, Fitch, or even the Littleton formation are present.

The upper contact of the Oliverian series is regionally concordant throughout the entire length of the Bronson Hill anticline, which is 150 miles long in New Hampshire. This contact is in the Ammonoosuc volcanics (Fig. 12). But the sheet of overlying Ammonoosuc volcanics ranges in thickness from a few tens of feet, as on the east flanks of the Swanzey dome, to several thousands of feet, as on the south flank of the Jefferson dome west of Randolph. Moreover, it is apparent that the formations found on the flanks of the domes — the Partridge, Clough, Fitch and Littleton formations — extended over the top of the domes prior to erosion. The relations on the plunging noses of the domes

imply this. Moreover, the graben associated with the Westmoreland dome offer particular pertinent information, because in all three graben the roof rocks are still preserved.

The foliation within the Oliverian series, most strongly developed near the contacts, is parallel to the bedding of the overlying formations. Near the center of some of the domes the foliation within the Oliverian series is horizontal (Billings, 1937, p. 534; Moore, 1949, Plate 1).

Some of the domes are relatively symmetrical, such as the Owls Head dome (Fig. 12), the Mascoma dome (section DD′, geological map), and the Jefferson dome (section BB′, geological map). Others, however, are overturned toward the west, notably the Smarts Mountain dome and Vernon dome (section FF′, geological map).

The Oliverian intrudes the overlying Ammonoosuc volcanics. In the Mt. Cube area, amphibolite belonging to the Ammonoosuc volcanics is injected by granodiorite sills up to 30 feet thick (Hadley, 1942, p. 141). In the Owls Head dome, as elsewhere, the contact cannot be precisely placed on a map because "it is impossible to decide whether certain outcrops should be considered the main body full of inclusions, or Ammonoosuc volcanics thoroughly injected by sills" (Billings, 1937,p. 501). On the south flank of the Jefferson dome the rocks of the Oliverian series contain inclusions of the Ammonoosuc volcanics (Billings, 1941, p. 896). North of Berlin, the rocks of the Oliverian series show sharp, chilled, knife-edge contacts against the Ammonoosuc volcanics; moreover, dikes of Oliverian penetrate the Ammonoosuc (Billings and Fowler-Billings, unpublished).

It is also significant that many of the domes are relatively broad, open folds compared to the tight folds in the Salmon Hole Brook syncline, the Walker Mountain syncline, the Gardner Mountain anticline, and the Merrimack synclinorium. This implies that the rocks in the core of the dome were relatively rigid bodies at the time of the final intense folding. The Oliverian series is thus pre-tectonic or early tectonic.

The origin of these domes is problematical (Billings, 1945, pp. 63-65; Eskola, 1949). Many suggestions have been made. One is that the Oliverian series consists of metamorphosed volcanic rocks similar to or identical with the Ammonoosuc volcanics. This seems unlikely because: (1) the Oliverian series and Ammonoosuc volcanics are distinctive units that can be separately mapped in the field; (2) the Oliverian, although much of it now has a granoblastic texture, was at one stage considerably coarser in grain than the Ammonoosuc volcanics; (3) although the Ammonoosuc is massive and unbedded in places, bedding can be recognized when sufficiently large areas are studied; (4) the Oliverian occurs in much larger units; and (5) intrusive contacts of the Oliverian indicate a molten rock.

A second suggestion is that the Oliverian is "granitized" Ammonoosuc, that is, volcanic rocks to which something has been added. But it is difficult to see how such a heterogeneous formation as the Ammonoosuc volcanics, even if metasomatically replaced, could produce a unit such as the Oliverian, which is relatively homogeneous over large areas.

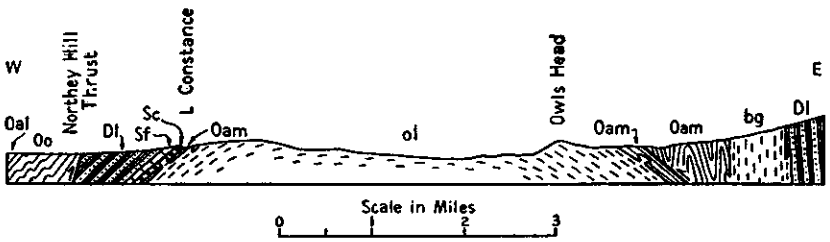

Figure 12. Owls Head Dome. Ordovician (?): *Oo* = Orfordville formation; *Oal* = Albee formation; *Oam* = Ammonoosuc volcanics. Silurian: *Sc* = Clough quartzite; *Sf* = Fitch formation. Devonian: *Dl* = Littleton formation. Middle or Upper Devonian (?): *ol* = Oliverian plutonic series; *bg* = Bethelehem gneiss of the New Hampshire plutonic series.

The intrusive and locally chilled contacts are more readily explained by the injection of magma. Certainly all the known facts can be explained in this way. The most plausible explanation is that the Oliverian represents a single, large, composite, sill-like sheet thousands of feet thick that resulted from the injection of several large sills and lenses of magma. This great sheet was later folded, a fact that will become more apparent after the structure of the Mt. Clough pluton has been discussed.

The map pattern suggests that the Lebanon granite occupies the core of a dome. A domical structure is also indicated by structure section DD′ on the geological map. The minor folds and lineation on the northern end of the Lebanon dome plunge northward. But the minor folds and lineation on the south end also plunge northward (Lyons, 1955, p. 127), indicating that this body is more like a cylindrical mass of granite, the axis of which

plunges north. Gravity data confirm this conclusion (Bean 1953, p. 533-534). Lyons (1955, p. 127-130) has recently shown that the Lebanon granite is a syntectonic granitic intrusion that was forcefully injected upward from the northwest toward the southeast, but that the intrusion was accompanied by extensive metasomatic replacement along its margins. The Lebanon may have been contemporaneous with the injection of the rest of the Oliverian series or it may be somewhat younger.

New Hampshire Plutonic Series

Mt. Clough pluton. The main body of the Mt. Clough pluton, composed of Bethlehem gneiss, extends from Franconia on the north to the vicinity of East Alstead on the south, a distance of 78 miles. The Bethlehem gneiss is somewhat granulated and, especially near the margins, is foliated. The contacts are generally concordant with the bedding and foliation in the adjacent sediments. North of Glencliff, 4 miles southwest of Mt. Moosilauke, the contacts of the Mt. Clough pluton and the foliation within it are vertical. Thus, in this area the pluton is a vertical sheet ½ to 3 miles thick (section CC′). South of Glencliff the foliation and the contacts dip toward the east at progressively lower angles. In the vicinity of Canaan (section DD′) the pluton dipping 35° E., is 1½ miles thick; a small outlier 1 mile northwest of Canaan lies on top of Ammonoosuc volcanics in a small syncline. The easterly dip continues (section EE′) to the south end of the body. At the south end of the pluton the metamorphosed sediments split around the intrusive, those on the west side striking slightly north of west, those on the east side striking north-northeast.

The base of the Mt. Clough pluton wraps around the south end of the Mascoma dome; a westerly protuberance of the pluton rests on the Clough formation in a syncline west of the dome. This, in turn, suggests that the two long bodies of Bethlehem gneiss west of the domes, one extending from Landaff to Pike, the other extending from Piermont Mountain to Lyme Center, are also outliers of the Mt. Clough pluton. That is, the pluton originally extended completely over the domes, but the connecting link has been destroyed by erosion (Billings, 1945, p. 61).

The Mt. Clough pluton is slightly discordant from east to west, because the base of the pluton on the east side of the domes rests on Ammonoosuc volcanics, locally the Clough or Fitch for-

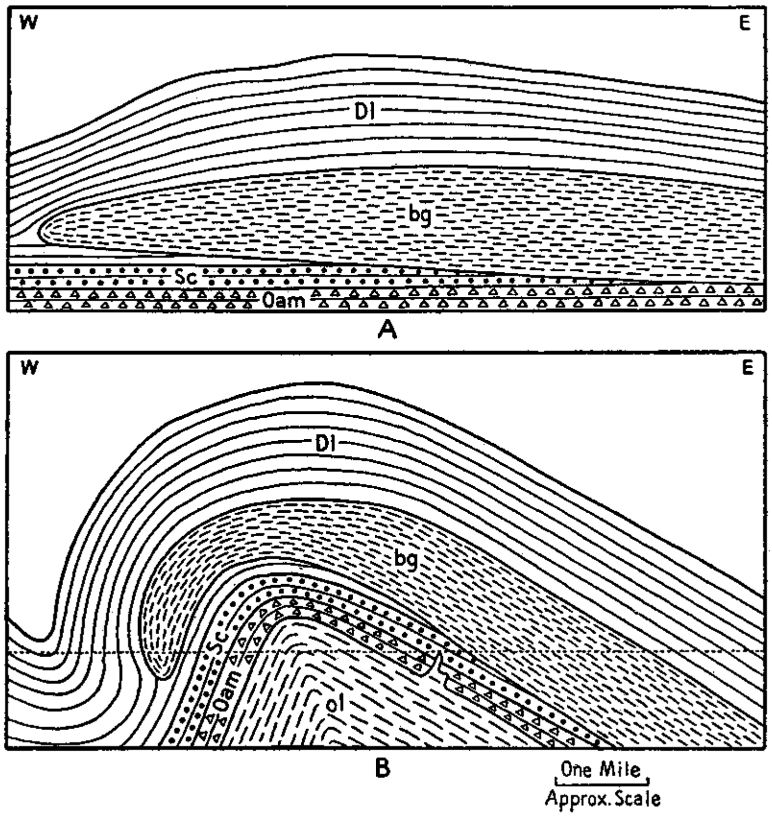

Figure 13. Evolution of Mt. Clough pluton. Ordovician: *Oam* = Ammonoosuc volcanics. Silurian: *Sc* = Clough quartzite. Devonian: *Dl* = Littleton formation. Middle or Upper Devonian (?): *ol* = Oliverian plutonic series: *bg* = Bethlehem gneiss of the New Hampshire plutonic series. A. After pluton was injected but before doming. B. After doming; broken line is present erosion surface.

mations, but west of the domes the base rests on the Clough, Fitch or Littleton formations. The large masses of Clough quartzite on Black Mountain, Mt. Cube, and Croydon Mountain have apparently been stripped off from what is now the east side of the domes, and, as the intrusive was moving westward, piled up on what is now the west side.

It is improbable that the Mt. Clough pluton was injected as a large, sickle-shaped body that came from the east, rose up over the domes, and then plunged down again on the west flank. A more plausible interpretation is that the pluton was injected as a horizontal sheet separated from the Oliverian series by a septum

composed of the Ammonoosuc, Clough and Fitch formations. The two were then folded together into a great arch (Fig. 13). The parallelism of the lineation in the Bethlehem gneiss and the adjacent Littleton formation has also been taken as evidence that the Mt. Clough pluton was involved in the deformation and hence is syntectonic (Billings, 1937).

The origin of the body of Bethlehem gneiss near the Connecticut River between Alstead and North Walpole is discussed below.

Mt. Cardigan pluton. This pluton, composed of Kinsman quartz monzonite, extends from Groton on the north to West Peterborough on the south, a distance of 72 miles. A large offshoot extends southwest near the south end of Sunapee Lake to East Alstead. In general, the contacts are concordant with the adjacent metamorphosed sediments; moreover, the foliation is essentially parallel to the contacts. At the north end this body is a sheet nearly 2 miles thick that dips 30° E. (section EE′). Further south, in the vicinity of Sunapee Lake, the western contact is steeper, dipping about 65° E. Still further south around Lovewell Mountain (Heald, 1950), the western contact of the main body and the western protuberance that extends to East Alstead dip 80° E. Locally, as near Stoddard, the western contact is folded.

North of Danbury the eastern contact dips about 50° E. Between Danbury and West Peterborough this contact has not been studied during the modern surveys of the geology of the state; consequently, the attitude is not known.

The Cardigan pluton is a body that was forcefully injected into the Littleton formation. A strong secondary lineation in the Mt. Cardigan area (Fowler-Lunn and Kingsley, 1937) indicates that this pluton was involved in the deformation of the adjacent sediments, hence is syntectonic.

Lincoln pluton. The Lincoln pluton, composed of Kinsman quartz monzonite, is named from the township of Lincoln; it is a large, lenticular body, the contacts of which are essentially vertical. The resistant schists and quartzites of the Littleton formation wrap around the south end of the body, holding up an arcuate ridge known as Mt. Kineo. Apparently this pluton has been forcefully injected into the surrounding rocks.

Rumney pluton. The Rumney pluton, also composed of Kinsman quartz monzonite, is named from the township of Rumney, in which the southwest end of the pluton lies; it is much more irregular than the Mt. Clough, Mt. Cardigan, and Lincoln plutons. Despite its irregularities it is generally concordant. The shape suggests a large lens that has been folded, but some of the minor irregularities may be the result of injections of apophyses into the surrounding schists.

Bellows Falls and Ashuelot plutons. The Bellows Falls pluton, composed of Bethlehem gneiss, is named from Bellows Falls, which lies across the Connecticut River west of North Walpole. It is a large sheet, 2,000 to 3,000 feet thick, overlain and underlain by the Littleton formation and lying in a synclinal basin. The Ashuelot pluton, composed of Kinsman quartz monzonite, lies in the southwest corner of the state. It is a sheet several miles thick that dips 50° E. (section FF′). A large mass of the Littleton formation near the east side of the body is apparently a large inclusion. The Ashuelot pluton is cut off on the east by the Triassic border fault.

One is tempted to suggest that the Bellows Falls and Ashuelot plutons are respectively displaced portions of the Mt. Clough and Mt. Cardigan plutons. If the Mt. Clough and Mt. Cardigan plutons were injected as great lenses, it is possible that in southern New Hampshire they moved further westward than they did further north.

Winnipesaukee pluton. The Winnipesaukee pluton, a composite body composed of Kinsman quartz monzonite (Meredith granite phase) and Winnipesaukee quartz diorite, is an irregularly circular body 24 miles in diameter. On the northwest side of the pluton the contact is concordant in plan (Moke, 1944). On the southwest side, north of Laconia, the strike of the foliation in the Kinsman quartz monzonite is parallel to the contact, but locally this contact cuts across the foliation of the Littleton formation (Quinn, 1941). Although the strike of the contact is parallel to the strike of the foliation between Tuftonboro and Center Tuftonboro, northeast of Wolfeboro Center the foliation in both the Winnipesaukee and in the Littleton is perpendicular to the contact. The contact has not been studied in the area between Winnisquam Lake and Holderness. The general concordancy of the body suggests that the Winnipesaukee pluton has been forcefully injected into the adjacent schists.

Binary granites. The binary granites, such as the Concord, Bickford, and Fitzwilliam, were injected under conditions rather different than those under which the previously described plutons were emplaced. In general, the bodies of binary granite are relatively small. The largest body shown on the map, the one south of Ossipee Lake, may be far more complex than shown, because the exposures in this area are not good. The binary granites are generally massive and lack the foliation and lineation found in the older plutons. Moreover, the contacts are in places difficult to delineate on a map, because the surrounding schists are cut by numerous dikes and sills of the binary granite. The country rocks were relatively brittle at the time of intrusion, in contrast to the more plastic conditions at the time of emplacement of the Bethlehem and Kinsman. West of the Presidential Range the structures of the Littleton formation wrap around the northeast end of the binary granite that extends northeasterly from Bretton Woods. This suggests that the body was forcefully injected (Billings, 1941, p. 918), but that the country rock was shattered by the intrusion and injection of numerous dikes and sills.

Plutonic Rocks of Southeastern New Hampshire

The plutonic rocks in the southeastern part of the state have not been as carefully studied as those elsewhere in the state. The coincidence of the Exeter diorite with an anticline suggests that the diorite was forcefully injected, dragging up the Kittery quartzite with it. Some of the bodies of granite in the area between Nashua and Portsmouth are characterized by a strong secondary foliation, indicating that they have been involved in deformation.

White Mountain Plutonic-Volcanic Series

General Statement. The White Mountain plutonic-volcanic series is structurally very different from the older series. The plutonic bodies are mostly discordant ring-dikes and stocks. Subsided blocks of volcanics, comagmatic with the plutonic rocks, are preserved in several places. Although the various bodies belonging to this series might be described geographically, it is more logical to follow an order that will reflect the structural development of the various plutons. Consequently, the bodies will be described in the following order: (1) ring-dikes within which subsided blocks of volcanics are preserved (Ossipee and Belknap

Mountains); (2) ring-dikes without subsided volcanics (Pliny-Pilot complex); (3) stocks (Cannon Mountain, Mad River, Baldface and other stocks); (4) small ring structures (Red Hill, Mt. Tripyramid, and Pawtuckaway Mountains); and (5) White Mountain batholith.

Ring-dikes with subsided volcanics. The Ossipee and Belknap Mountains belong in this category. The structure of the Ossipee Mountains, the most striking of the cauldron subsidences in New Hampshire, is illustrated in Figure 14E. A ring-dike of porphyritic quartz syenite (Albany) that encircles the mountain has essentially vertical contacts. Inside the ring-dike is the subsided block of Moat volcanics. A central stock of Conway granite is 5 miles in diameter.

The evolution of the Ossipee Mountains is shown in Figure 14. During the Mississippian (?), when the magmas of the White Mountains type became available, large quantities of lava were erupted to form the Moat volcanics (Fig. 14A). As time progressed, the magma reservoir approached closer to the surface of the earth. When the top of the magma reservoir came within 3 miles, more or less, of the surface, a vertical fracture, circular in plan, formed over the reservoir (Fig. 14B). The block isolated by this fracture settled into the reservoir and some of the magma was intruded into the fracture to form the ring-dike (Fig. 14C). The magma made room for itself, in part by piecemeal stoping, along the ring-fracture. It is believed that the outer edge of the subsided block sank at least 4,500 feet, whereas that the center went down at least 11,000 feet (Kingsley, 1931). The subsided block was broken into subsidiary blocks by radial faults. In a later stage another great block sank (Fig. 14D) and more magma was intruded to form the Conway granite. Later erosion resulted in the present topography (Fig. 14E). Obviously the structural evolution was more involved than can be shown in a series of simple diagrams such as Figure 14. For example, the surface upon which the Moat volcanics were erupted may have possessed considerable relief. Moreover, erosion and volcanism were undoubtedly going on during the various intrusive stages.

The Belknap Mountains evolved in a similar way, but had a much more complex history in detail. In addition to the ring-dike of porphyritic quartz syenite, there are other incomplete ring-dikes composed of monzonite, syenite, quartz syenite, and Conway

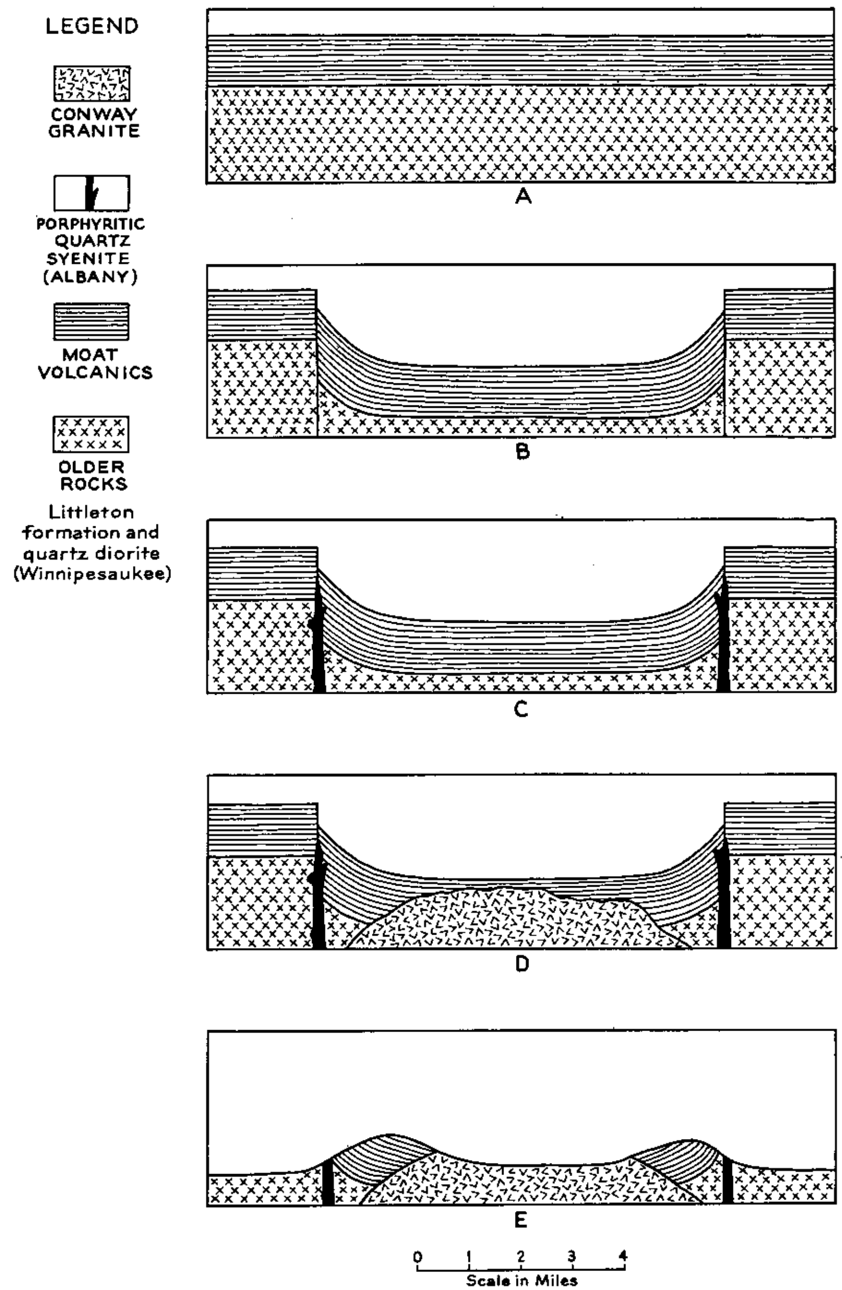

Figure 14. Origin of Ossipee Mountains. See text. After A. P. Smith, L. Kingsley, and A. Quinn.

granite. The central stock is also more complex than in the Ossipee Mountains, being composed of diorite, syenite, and Conway granite. The Moat volcanics, preserved only on the south side of the complex, have been almost completely eliminated by the emplacement of the central stock. Moreover, the intrusions are related to three different centers, which are progressively younger to the northwest (Modell, 1936). The syenite, monzonite and some of the quartz syenite ring-dikes are concentric about a center 1½ miles south of West Alton. The ring-dikes of porphyritic quartz syenite and Conway granite are concentric about a center 1½ miles southwest of West Alton. The center of the central stock is about 2 miles west of West Alton. Finally, late in the evolution, a volcanic vent broke through the northwest part of the complex.

Ring-dikes without subsided volcanics. This type of structure is illustrated by the Pliny-Pilot complex, which consists of two parts, the northern Pilot complex and the southern Pliny complex. The ring-dikes and stocks of the Pilot complex are related to several centers. The most westerly ring-dike, the Cape Horn, is concentric about a center in the northern part of the Pilot Range. The ring-dikes of the Pilot Range are concentric about a center 2 miles east of the Pilot Range. The scalloped borders of the stock of Conway granite suggests that it consists of 3 separate stocks that coalesced to form a single body that clearly truncates the ring-dikes.

The ring-dikes of the Pliny complex (section BB′) are concentric about a center 2 miles northeast of the highest part of the Range. The Crescent Range ring-dike is concentric about this center or one further to the east.

Stocks. Numerous stocks, composed exclusively or chiefly of Conway granite, are shown on the map. Although the contacts of most of these stocks are generally steep, on the north side of the Mad River stock (Fig. 11) the schists on the summit of Mt. Tecumseh form a flat cap on top of the Conway granite (Moke, 1944). These stocks, like those in the Ossipee Mountains and in the Pilot-Pliny complex, were emplaced when a large block subsided into a magma reservoir, the magma rose, and filled the potential cavity (Billings, 1945, p. 54-55).

Small ring structures. Four small ring structures are similar to the large ring structures except for size. These are found on Mt. Tripyramid, Red Hill, Rocky Mountain west of Alton Bay,

and the Pawtuckaway Mountains. Most of the contacts within these bodies are steep, most are sharp, but a few are gradational. There is no systematic change in mineralogy or chemistry from the interior of these bodies to the outer edge. On Mt. Tripyramid the distribution of rocks from the interior outward, which is not shown in complete detail on the geological map because of scale, but is shown in Fig. 15 F, is as follows: (1) quartz syenite, (2) monzodiorite, (3) pink monzonite, (4) gray monzonite, (5) quartz monzonite, and (6) on the west side, gabbro. The order of age seems to be: (6), (2), (4), (3), (5) and (1). At one locality a small screen of basalt about 30 feet wide lies between Nos. (4) and (5). On Red Hill the distribution from the interior outward is: (1) Conway granite, (2) medium-grained syenite, (3) nephelite-sodalite syenite, and (4) coarse syenite; two small bodies of quartz syenite are eccentrically placed. The order of age appears to be: (4), (3), (2) and (1). In the Pawtuckaway Mountains the distribution from the interior outward is (1) monzonite, (2) diorite, and (3) monzonite. Number (2) is the oldest, whereas (1) and (3) are younger.

The outer monzonite in the Pawtuckaway Mountains appears to be a small ring-dike concentric about a funnel-shaped mass of diorite (section EE′). The individual bodies on Red Hill and Mt. Tripyramid are presumably small ring-dikes intruded around a small, subsiding, steep-sided block shaped like an inverted cone (Fig. 15).

White Mountain batholith. An analysis of the map of the White Mountain batholith shows that it possesses all the structural features found in the ring-dike complexes and stocks. A large screen composed of the Littleton formation and the Kinsman quartz monzonite, extending from Rocky Branch through Notchland to the headwaters of the Swift River, divides the batholith into two parts.

The ring-dike complex comprising the western part of the batholith is oval in shape, 16 miles across in a north-south direction, and 12 miles in an east-west direction. The center is halfway between Mt. Carrigain and Mt. Bond. The longest ring-dike, composed of porphyritic quartz syenite, extends for 18 miles on the northwest side of the batholith around 120° of the oval. A possible continuation lies on the southeast flanks of Mt. Carrigain. A ring-dike of granite porphyry 6 miles long holds up Fran-

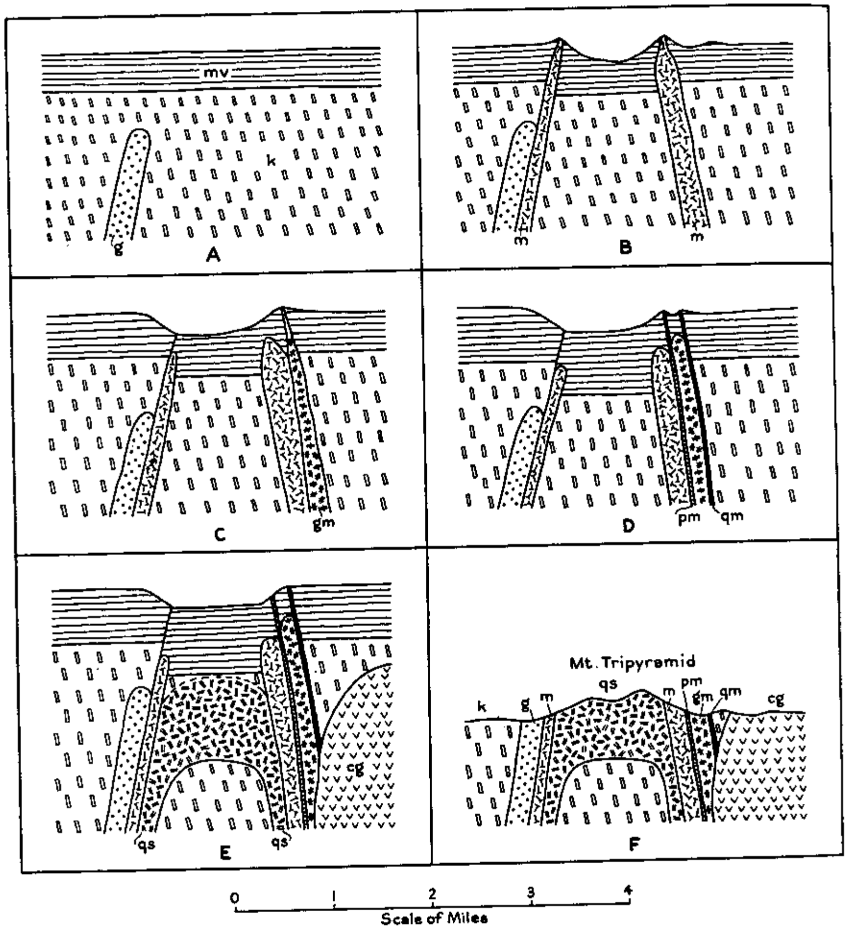

Figure 15. Origin of Mt. Tripyramid. k = older rocks (Littleton formation, Kinsman quartz monzonite, and quartz monzonite of Norway Rapids); mv = Moat volcanics; g = gabbro and hypersthene diorite; m = monzodiorite; gm = gray monzonite; pm = pink monzonite qm = quartz monzonite; qs = quartz syenite. After A. P. Smith, L. Kingsley, and A. Quinn.

conia Ridge on the west side of the batholith. A large arcuate mass of Mt. Osceola granite lies on the southwest side of this western part of the batholith. On the northeast and southeast sides of the oval, small dikes of quartz syenite and granite porphyry form part of the ring structure. Two ring-dikes of Conway granite coalesce with satellitic stocks; one of these is in the vicinity of Big Coolidge Mountain, the other is southeast of Twin

Mountain. A small mass of the Moat volcanics, resting unconformably on the Littleton formation, is preserved on Mt. Hale in the northern part of this ring-dike complex. Two other patches are preserved within the granite porphyries in the northwest part of the complex.

In the eastern part of the White Mountain batholith, two large, subsided blocks of Moat volcanics are preserved, one on Moat Mountain (section CC′), the other on Pequawket Mountain. Both of these bodies are partially enveloped by ring-dikes of porphyritic quartz syenite. A ring-dike of porphyritic quartz syenite also extends from Jackson to the Rocky Branch. Apparently each of these three ring-dikes is concentric about a separate cauldron subsidence, but inasmuch as the largest is only 6 miles in diameter and the smallest is only 2 miles in diameter, they are considerably smaller than the ring-dikes associated with the cauldron subsidences in the western part of the White Mountain batholith or the Ossipee Mountains. The largest, however, is comparable to those in the Belknap Mountains. The rest of the eastern part of the White Mountain batholith is probably composed of coalescing stocks. The southern part is certainly so constituted; a stock of syenite holds up Mt. Passaconaway, a stock of Conway granite surrounds Wonalancet, and the Mt. Tripyramid stock has already been described.

METAMORPHISM

General statement. It has long been known that in some parts of orogenic belts the original minerals have recrystallized, often into new mineral assemblages. A limestone composed of small calcite crystals may recrystallize into a marble composed of fewer but larger calcite crystals. A quartzose dolomite may recrystallize into a rock composed of diopside accompanied by some quartz or dolomite; carbon dioxide escapes in the process. A shale may recrystallize to a coarse schist composed of mica, quartz, feldspar, garnet, and sillimanite. Inasmuch as sedimentary rocks form under conditions of relatively low temperature and pressure, it has long been realized that metamorphism is related to conditions that differ from those normally existing at the surface of the earth.

The factors that must be considered in studying metamorphic rocks are temperature, lithostatic pressure, the vapor pressure of volatiles (especially H_2O and CO_2), and possibly stress (Turner and Verhoogen, 1951; Thompson, 1955). It appears likely, however, that stress, although influencing the texture and structure of the rocks that develop during metamorphism, has no effect on the mineral assemblages that are stable.

Metamorphism is often classified into two major categories. Regional metamorphism affects large areas and is characteristically associated with folding. Contact metamorphism is confined to the vicinty of plutonic rocks and is not associated with folding. However, the regional metamorphism so well displayed in New Hampshire is related to bodies of plutonic rocks, as will be shown below.

The ensuing pages will be clarified by a brief discussion of one example, the aluminum silicates (Thompson, 1955). The exact temperatures and pressures (Fig. 16) at which the reactions take place are not now known. Moreover, it is assumed that the only oxides present are Al_2O_3, SiO_2, and H_2O. If metamorphism were to occur at a lithostatic pressure represented by line *a*, hydrous aluminum silicates, such as pyrophyllite or kaolinite, would be stable at the lower temperatures. If the temperature increases, kyanite forms at the expense of the hydrous aluminum silicates. At still higher temperatures kyanite becomes unstable, and sillimanite becomes the stable form. In New Hampshire, as in most other areas, because of the presence of other oxides, muscovite forms instead of pyrophyllite or kaolinite, and staurolite usually forms instead of kyanite. If, however, the lithostatic pressure were that represented by the line *b*, kyanite would not form; instead, andalusite would crystallize when the hydrous aluminum silicates were no longer stable. Sillimanite would form at still higher temperatures.

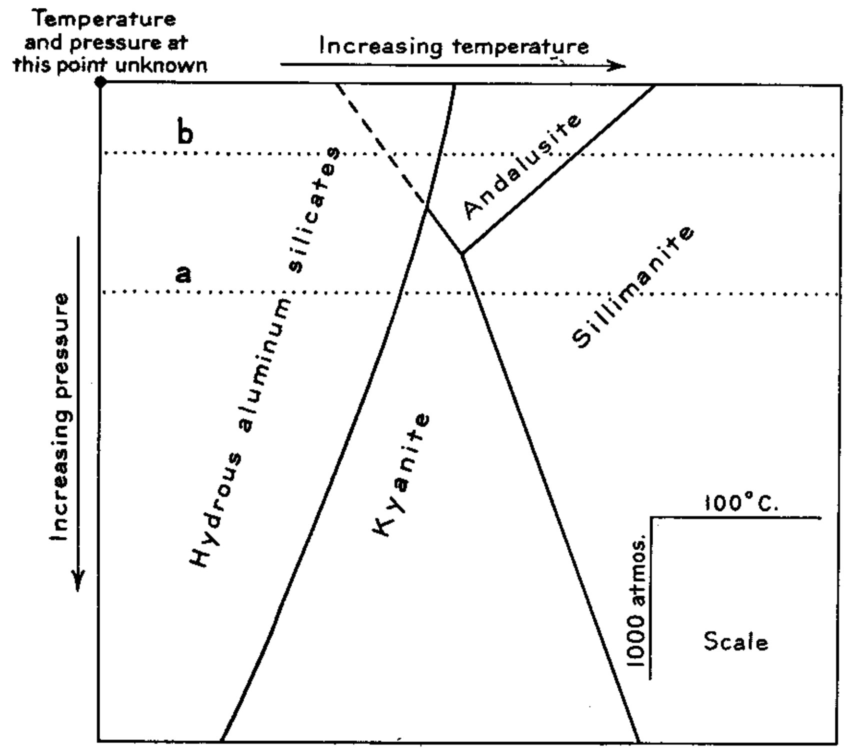

Figure 16. Possible stability relations for aluminum silicates in regional metamorphism. After J. B. Thompson.

Isograds. Four isograds are shown on the geological map: they are the biotite, garnet, staurolite, and sillimanite isograds. Thus, the metamorphic rocks of New Hampshire may conveniently be assigned to five metamorphic zones — the chlorite, biotite, garnet, staurolite, and sillimanite zones. The garnet isograd, for example, joins all those points in the field where garnet first appears as one progresses from an area where the metamorphism is of lower grade to those areas where the metamorphism is of higher grade. Strictly speaking, the isograds are inclined surfaces, and in the field we trace the intersection of this surface with the surface of the earth. The isograds are based on rocks that were originally shale. Theoretically, of course, an isograd could be drawn for every new mineral that appears or disappears as metamorphism increased; that is, an isograd could be drawn for every reaction. For example, under uniform lithostatic pressure, dolomite and quartz react to form actinolite and calcite when the temperature rises sufficiently; the CO_2 escapes. At still higher temperatures, the actinolite and calcite react with whatever quartz is available to form diopside. Thus, actinolite and diopside isograds could be drawn. But this actinolite isograd is different from the actinolite isograd in mafic rocks, which forms under less intense metamorphic conditions. Under sufficiently high temperature, muscovite breaks down into sillimanite, orthoclase and water. An "orthoclase" isograd has been mapped in the Lovewell Mountain quadrangle (Heald, 1950). But if an isograd were shown for every reaction, the description of the geology would become completely unmanageable.

The facies classification is theoretically more flexible than the zonal system, because it takes account of two variables — temperature and pressure. If the facies are based on one isochemical series, several facies can be establishd. But a different group of facies could be established for each isochemical series. Just as in the zonal system, each appearance or disappearance of a mineral would necessitate the establishment of a new facies.

To limit the number of metamorphic zones or facies on a geological map is perfectly justifiable cartographic procedure. Even in areas of unmetamorphosed rocks it is impossible to show every difference in lithology. For mapping purposes it is necessary to group the strata into formations, sometimes on a rather arbitrary basis. Similarly, it is permissible in discussing zones or facies to group together rocks that formed under somewhat similar but not identical conditions of temperature and pressure.

In analyzing the regional metamorphism in New Hampshire, differences in lithostatic pressure are not too significant. Firstly, if the boundaries separating different mineral phases were vertical on a diagram such as Fig. 16, lithostatic pressure could be completely neglected. Available experimental data and thermodynamic considerations show that these boundaries, although not vertical, are generally steep; hence, changes in temperature are far more important than changes in pressure. Secondly, in New

Hampshire the metamorphism is unrelated to the stratigraphic position of the formations. West of the Ammonoosuc thrust in the west-central part of the state, all the formations from the Orfordville to the Littleton formation lie in the chlorite zone, or, locally, in the biotite zone. Between the Ammonoosuc and Northey

LITHOLOGY OF VARIOUS ISOCHEMICAL SERIES IN DIFFERENT METAMORPHIC ZONES

ORIGINAL ROCK	ZONE					
	Chlorite	Biotite	Almandite	Staurolite	Sillimanite	"Orthoclase"
Shale	Slate	Biotite phyllite	Biotite-garnet phyllite	Biotite-garnet staurolite schist	Sillimanite schist or gneiss	Porphyroblastic orthoclase gneiss
Argillaceous sandstone	Argillaceous sandstone	Quartz-mica schist	Quartz-mica-garnet schist			
Quartz sandstone	Quartzite					
Limestone	Limestone	Marble				
Quartzose dolomite	Quartzose-dolomite		Actinolite-calcite granulite		Diopside (-actinolite) granulite	
Basalt	Chlorite-epidote-albite schist (may have actinolite)		Albite-epidote amphibolite	Amphibolite		
Rhyolite	Rhyolite	Fine-grained biotite gneiss				

Figure 17. Lithology of different isochemical series in various metamorphic zones.

Hill thrusts, between Littleton and Orfordville, all these same formations lie in the staurolite zone. Southeast of the Mt. Clough pluton the Littleton formation, despite the fact that it is the highest stratigraphic unit, lies in the sillimanite zone. The Orfordville formation in extreme western New Hampshire is in the biotite zone, although it is 25,000 feet stratigraphically lower than the highest beds in the Littleton formation. It is obvious, therefore, that differences in lithostatic pressure are not the cause of the diversity in the grades of metamorphism. We conclude, therefore, that the chief cause of these dissimilarities is a difference in temperature.

The vapor pressures of water and carbon dioxide are additional variables that influence the mineralogy of rocks undergoing metamorphism (Thompson, 1955). This is a factor that is difficult to evaluate at the present time, because of a lack of adequate experimental data. But some apparently anomalous mineral assemblages in New Hampshire may be related to vapor pressure. But field data in New Hampshire indicate that such a factor would at the most modify only slightly the concept of broad zones separated by isograds.

Mineralogy of each isochemical series. In the earlier sections of this report the lithology of each formation has been described. Although some formations are found in one metamorphic zone, others appear in as many as five zones. It is now desirable to summarize these lithological differences in the various zones by tracing the changes in several isochemical series. This is done in Fig. 17. Shaw (1954) has shown that the minor elements in the Littleton formation in general do not differ greatly in the different metamorphic zones.

Time of regional metamorphism. The regional metamorphism in New Hampshire appears to have taken place at essentially one time in geological history. The independence of the grade of metamorphism from stratigraphic position is one indication of this. The relatively simple pattern shown by the isograds is a second indication. Finally, there is nothing in the mineral paragenesis to suggest two or more widely separated periods of regional metamorphism. Of course, the metamorphic evolution was complex and lasted for a long time. Although much of the metamorphism accompanied the deformation, some rocks, such as the granular gneisses of the Littleton formation in the Gorham area (Billings and K. Fowler-Billings, unpublished) underwent final recrystallization after the deformation ceased.

It is also clear that the metamorphism was closely related in time with the injection of many of the larger bodies of the New Hampshire plutonic series, notably the Bethlehem gneiss and the Kinsman quartz monzonite. The foliation and lineation in these rocks are partially the result of external forces acting on these bodies. The parallelism of the lineation in the Bethlehem gneiss and the adjacent metamorphic rocks (Billings, 1937, p. 537) shows that all these rocks were involved in the same deformation and metamorphism. The garnet found in the Kinsman quartz monzonite in places (Heald, 1951) is the result of metamorphism. The binary granites of the New Hampshire plutonic series, however, were younger than the metamorphism.

Cause of the metamorphism. As indicated above, the diversity in the grades of metamorphism appear to be largely the result of differences in temperature. Heat resulting from defor-

mation is an inadequate explanation, partly because there is no evidence that the most highly metamorphosed rocks are any more folded than the least metamorphosed rocks. On the other hand, heat from rising masses of magma seems a plausible cause of the metamorphism. Certainly, throughout much of New Hampshire the grade of metamorphism is related to the presence or absence of large bodies of the New Hampshire series. This becomes even more striking if one looks at a geological map of New England. In New Hampshire the principal exception to the generalization is in the Merrimack synclinorium between Lake Winnipesaukee and Concord. But even here, small bodies of pegmatite are present, suggesting that larger plutonic bodies are at no great depth. The manner in which the grade of metamorphism decreases southeast of the Fitchburg pluton is striking. On the other hand, there is no evidence of an increase in the grade of metamorphism around the diorites of southeastern New Hampshire, notably the diorite of the Exeter pluton. This suggests that the presence of a hot mass of magma was, by itself, not sufficient. Transfer of heat by conduction was presumably too slow. But heat was readily transferred by solutions emanating from more volatile-rich siliceous intrusions.

Retrograde metamorphism. The term "retrograde metamorphism" is used for those cases in which minerals of presumed lower grade have replaced minerals of higher grade. No genetic theory is here implied by the term. Retrograde metamorphism along the Ammonoosuc thrust has been described by Hadley (1942, page 172). He says that southeast of the Ammonoosuc thrust in the Mt. Cube area many of the minerals characteristic of the staurolite zone have been replaced. Biotite has been completely replaced by chlorite for 1,000 feet southeast of the thrust, garnet has similarly been completely replaced by chlorite for 300 feet southeast of the thrust, and staurolite and kyanite are represented only by pseudomorphs for 800 feet from the thrust. White and Billings (1951, p. 690) made similar observations in the Woodsville quadrangle, but say that fresh biotite may be found within 500 feet of the fault, fresh staurolite within 200 feet, and fresh garnet within 70 feet. Lyons (1955, p. 139) says that in the Hanover quadrangle the band of retrogression is narrower, in places only a few feet wide. All observers agree that the retrogression along the Ammonoosuc thrust is caused by the infiltration of water along fractures associated with the fault; in this sense, it is hydrothermal alteration, presumably under considerably lower temperature than those that prevailed during the regional metamorphism.

Low-grade minerals are found in many of the rocks of higher grade, notably those in the staurolite and sillimanite zones. In many cases it can be shown that higher grade minerals have been replaced by lower grade minerals, such as chlorite after biotite and garnet, sericite after andalusite, or biotite after chlorite. Many of these processes involve addition of water, presumably from some source external to the rocks concerned. Some of the retrogression probably represents changes in the waning stages of the regional metamorphism. Lyons (1955, p. 169) has suggested that in the Hanover area the retrogression, because it affects diabase dikes of the White Mountain series, is distinctly later than the regional metamorphism. Another idea that should be considered in New Hampshire is the possibility that some of the "low-grade" minerals were actually in equilibrium with the "high-grade" minerals because of an unusually high vapor pressure of water.

Contact Metamorphism. Contact metamorphism has not been described from many localities in New Hampshire. *A priori*, one would expect such metamorphism related to the White Mountain series, expecially because it has been described from Ascutney Mountain in easternmost Vermont, 8 miles northwest of Claremont (Daly, 1903, p. 22-35). But in New Hampshire the contact metamorphism might be difficult to recognize because most of the bodies of the White Mountain series were injected into older plutonic rocks or into metamorphic rocks that had already attained the sillimanite zone of metamorphism. A classic example of tourmalinization of the Littleton formation in contact with the Albany porphyritic quartz syenite in Crawford Notch was described many years ago (Hawes, 1881). Moke (1948, p. 119-123) states that around the Mad River stock, composed of Conway granite, andalusite, chlorite, sericite and muscovite are more abundant than elsewhere in the Littleton formation. Billings (1928, p. 79) describes hornfels from the North Conway quadrangle. Some of the blocks of andalusite phyllite in the Moat volcanics in this area may be contact metamorphosed rocks.

GENESIS OF THE PLUTONIC ROCKS

Comparison of the Major Paleozoic Plutonic Series

Of the seven series into which the plutonic rocks of New Hampshire have been classified, two, the pre-Cambrian (?) Newburyport quartz diorite and the Ordovician (?) serpentine, are areally unimportant. The five principal series, the Highlandcroft, Oliverian, New Hampshire, Hillsboro (southeastern New Hampshire), and White Mountain, show many contrasts in structure, texture, and mineralogy. The five series are compared and contrasted with one another in Table 10. Such a table, although necessarily somewhat abbreviated, is better than long descriptions, because the various features can be readily compared.

It should be emphasized that the grouping of the plutonic rocks of New Hampshire into various plutonic series in based primarily on chronology, especially the relationship of the plutonic rocks to the surrounding sedimentary and volcanic rocks, the relationship to the deformation, and the relationship to the metamorphism. This is re-emphasized in line 1 of Table 10. The Highlandcroft plutonic series is older than the unconformity at the base of the Silurian rocks. Conversely, much of the White Mountain plutonic-volcanic series is younger than the unconformity between the Devonian and the Mississippian (?) Moat volcanics. The Oliverian, New Hampshire, and Hillsboro (southeastern New Hampshire) series were emplaced after the formation of the older of these two major unconformities but prior to the formation of the second unconformity. The Oliverian series is considered somewhat older than the New Hampshire series because of structural and textural features.

Whereas, as shown in line 2 of Table 10, the White Mountain series is younger than the regional metamorphism, the New Hampshire and Hillsboro series are in part synchronous with the regional metamorphism, the Oliverian is probably somewhat older, and the Highlandcroft, being pre-Silurian, is much older.

Whereas the White Mountain series, as shown in line 3, is accompanied by consanguineous volcanics, such rocks have not been found associated with the other principal series.

The differences in foliation, lineation, and texture are brought out in lines 4, 5, and 6.

Pegmatites associated with the New Hampshire, Hillsboro, and Oliverian series are exceedingly common (Cameron et al., 1945, 1954). Those associated with the New Hampshire series are believed to be white, whereas those associated with the Oliverian series are considered to be pink; this distinction, however, has not been adequately demonstrated in the field. Pegmatites associated with the Highlandcroft and White Mountain series are very rare. The mineralogy of those associated with the White Mountain series has been described by Gillson (1927).

The contrasts in mineralogy are shown in that part of the table under line 10.

Origin of the Plutonic Rocks

Theories

The origin of plutonic rocks is a controversial subject. Consequently, before discussing specific problems in New Hampshire, it is desirable to review briefly the present theories on the origin of plutonic rocks.

One hypothesis is that plutonic rocks consolidate from magma. How this magma may have formed is of no direct concern. Nor, for the present, are we concerned with the mechanics of emplacement of the magma, whether by forceful injection or by magmatic stoping.

A second hypothesis is that plutonic rocks, forming in place from sedimentary or volcanic rocks, remain solid or almost completely solid throughout the process. In other words, the plutonic rocks are merely highly metamorphosed sedimentary or volcanic rocks. This is not a new idea; in fact, Hitchcock (1877) assumed that most of the plutonic rocks of New Hampshire formed in this way. This metamorphism could take place with little or no change in chemical composition. Moreover, although the rocks would, in many instances, remain solid throughout the transformation, a stage could be reached when some of the lighter-colored constituents would become partially molten and segregate into layers and lenses.

A variant of this second hypothesis assumes that changes in chemical and mineral composition result from the introduction of elements from outside sources. This material could be introduced by aqueous solutions, or, as some have proposed, the elements may travel as ions that diffuse through the rock. The rock may remain solid throughout these changes or it could become partially fluid.

Some plutonic series, such as the White Mountain series, consist of a large variety of rocks. Despite the fact that the end members are widely divergent in chemical and mineralogical composition, the progressive, systematic differences within the intermediate members show that all the rocks are related. That is, they are a consanguineous or comagmatic series. For example, despite the fact that the end members may be gabbro and granite, various intermediate members indicate that all the rocks are related. It is generally agreed that such divergent, consanguineous rocks evolved from one or two magmas. The various theories of magmatic evolution can be only briefly listed here (Turner and Verhoogen, 1951, p. 66-76): (1) magmatic differentiation, which may be accomplished by (a) fractional crystallization, (b) gaseous transfer, (c) liquid immiscibility; (2) assimilation of older rocks; or (3) mixing of two magmas, such as basaltic and rhyolitic magmas.

In testing these various theories in New Hampshire, one should keep the various facets of the problem clearly separated. One problem is whether the plutonic rock consolidated from magma or is the result of the recrystallization of a sedimentary or volcanic rock, with or without change in chemical composition. A second problem is whether the rock is autochthonous or allochthonous; that is whether it formed in place or came from some distant source. We commonly assume that magma comes from deeper within the earth, but it is possible, although exceedingly unlikely, that a magma could have formed from a solid rock in the very spot where we now see the plutonic rock. Conversely, a granitized sediment might remain in place, or it could move a considerable distance from its original stratigraphic position.

A third problem, if the rock has moved into place from a distant source, is that of emplacement; that is, whether by stoping, forceful injection, or permissive injection. By permissive injection is meant the introduction of magma into a potential void that is being opened up by tectonic processes.

In the ensuing discussion, an attempt will be made to keep these various problems separated.

White Mountain Plutonic-Volcanic Series

The White Mountain plutonic-volcanic series has consolidated from magma. The Moat volcanics, 10,000 feet thick, demonstrate that large quantities of magma were available to erupt as flows and pyroclastic rocks. The hypidiomorphic granular texture of the plutonic rocks of this series indicates that they consolidated from magma. The structural relations of these rocks, forming discordant bodies, such as ring-dikes, stocks, and a batholith, indicate magmatic rocks. Finally, the systematic differences in the mineralogy of these rocks indicate a magmatic origin and especially that fractional crystallization played an important role in the formation of the magmas. The series became progressively more siliceous with time, progressing from gabbro through diorite, monzonite, syenite, and quartz syenite to granite. Simultaneously, the ratio of iron to iron plus magnesia became progressively higher in the dark minerals, along with an increase in the ratio of potash feldspar to total feldspar. Chapman and Williams (1935) believed, however, that fractional crystallization of basalt was quantitatively insufficient to produce the large quantities of quartz syenites and granites in the White Mountain series, and suggested that large amounts of older siliceous rocks were assimilated into the basalt. It was this syntectic magma that underwent fractional crystallization.

New Hampshire Plutonic Series

Most of the binary granites of the New Hampshire plutonic series were emplaced after the climax of the Acadian revolution. The manner in which many of these bodies cross-cut the older rocks as dikes and sills is indicative of moving magma. Moreover, the hypidiomorphic granular texture suggests consolidation from magma. Finally, perhaps the most compelling evidence is the fact that these rocks have a remarkably uniform composition (Chayes, 1952) near that of the granite ternary eutectic predicted by theory for crystallization from a melt.

The Bethlehem gneiss has been considered by most observers to be magmatic. Although the texture is granoblastic in many places, locally it is hypidiomorphic granular, suggesting consolidation from magma. Moreover, although it is regionally concordant, lying near the base of the Littleton formation, the Bethlehem gneiss in the Mt. Clough pluton is locally discordant, as described in the section on structure. C. A. Chapman (1952) has recently concluded that the Bethlehem gneiss is a granitized sediment.

The Kinsman quartz monzonite was considered to be a metamorphosed sediment by C. H. Hitchcock (1877). But nearly sixty years ago, Daly (1898) showed that the Kinsman is intrusive, a

conclusion that has more recently been adhered to by Billings (1937) and Heald (1950). Dikes and sills of the Kinsman intrude the adjacent schists. Moreover, plutonic breccias composed of the Kinsman and the older rocks are observed locally (Moore, 1949). Where least deformed, the Kinsman shows a hypidiomorphic granular texture.

Similarly, the quartz diorites are considered to be magmatic. Where not granoblastic due to deformation, the texture is hypidiomorphic granular. Locally, as in the Gorham quadrangle (Billings and Fowler-Billings, unpublished), dikes and sills of quartz diorite cut the metamorphic rocks. Northwest of Squam Lake the Littleton formation wraps around the Winnipesaukee quartz diorite, indicating forceful injection.

The origin of the magmas of the New Hampshire series is problematical. Although they may be differentiates from basalt, they may equally well be melted up older rocks or granitized sediments that moved up from greater depths.

Oliverian Plutonic Series

Although most published papers have considered the Oliverian plutonic series to be magmatic, numerous facts have suggested to some geologists that these rocks are of a different origin. One theory is that the series consists of Ammonoosuc volcanics that have been metamorphosed with little change in composition. A variant of this theory assumes that changes in chemical composition accompanied the metamorphism. Facts suggesting to some observers that the Oliverian consists largely of metamorposed volcanic rocks, with or without addition of material, are the following. (1) The chemical composition is similar to that of volcanic rocks, especially rhyolites, quartz latites, and dacites (see Tables 3 and 7). (2) The rocks in some places show slight differences in mineralogy and chemical composition in layers that are parallel to the foliation; this suggests bedding parallel to the foliation. (3) Dikes of the Oliverian cutting the adjacent rocks are rare. (4) Large microcline "phenocrysts" are subhedral, lacking the granoblastic textures characteristic of the plagioclase and quartz; this suggests to some that the microcline was introduced subsequent to the granulation of the rock (C. A. Chapman, 1939). (5) The regionally concordant character of the upper contact of the Oliverian series is more readily explained if the series is a metamorphosed sheet of volcanic rocks.

Facts suggesting to other observers that the Oliverian is premagmatic are the following. (1) Dikes, although rare, are present. (2) The Oliverian in places is in sharp contact with the Ammonoosuc, and the two units can be readily distinguished (Billings and Fowler-Billings, unpublished). (3) Plutonic breccias, consisting of blocks of older rocks that float in the Oliverian, although rare, are not lacking (Hadley, 1942, p. 141; Billings, 1943, p. 898). (4) Although a crude compositional banding parallel to the foliation may be observed, the rocks of the Oliverian series are relatively homogeneous over large areas.

The Oliverian series shows considerable range in composition: amphibolite, quartz diorite, granodiorite, quartz monzonite, granite and syenite. This series may be a product of the fractional crystallization of basalt, but other possibilities cannot be disproved at present.

Highlandcroft Plutonic Series

The Highlandcroft plutonic series is considered to be magmatic. Although locally showing foliation because of later deformation, the rocks typically possess a hypidiomorphic granular texture, indicating consolidation from a melt. Moreover, dikes of the Highlandcroft series cut the older rocks. Plutonic breccias, especially where the Highlandcroft is associated with the Albee formation around Lancaster, have developed. Readily observed in the field on a small scale, these features are shown on a larger scale near Lancaster on the geological map, where several large areas of the Albee formation are completely surrounded by rocks belonging to the Highlandcroft series.

GEOLOGIC HISTORY

General statement. Because of a paucity of fossils, the geological history of New Hampshire cannot be discussed in the same detail as is possible in highly fossiliferous areas. Partly for this reason, partly because of the lack of space, only a general sketch of the evolution of the stratigraphic units will be given here. Although the author is tempted to draw paleogeographic maps to illustrate this evolution, such maps would be premature.

Pre-Cambrian. Evidence bearing on the pre-Cambrian history of New Hampshire is indeed scanty. The Newburyport quartz diorite, now found only in the extreme southeast corner of the state, was injected, probably in pre-Cambrian time, into older metamorphic rocks that are preserved in Massachusetts (Emerson, 1917, p. 24-26, 28-32). Evidence from the Green Mountains of Vermont similarly shows that granitic rocks were injected into older metasediments during the pre-Cambrian. The pre-Cambrian basement beneath New Hampshire may have been rather thoroughly destroyed by younger intrusions during Paleozoic time.

Cambrian (?) and Ordovician (?). Sometime during the Cambrian and Ordovician, clastic sediments and volcanic rocks accumulated in New Hampshire. In the western part of the state these deposits are represented by four formations (Orfordville, Albee, Ammonoosuc, and Partridge formations) and probably by three additional formations (Waits River, Standing Pond, and Gile Mountain formations). The total accumulation amounted to more than 20,000 feet. If the age assignments tentatively made in this paper are correct, all this deposition took place in Middle and Late Ordovician times. However, the Orfordville, Albee, Ammonoosuc and Partridge formations, although in part Middle Ordovician, may be as old as Lower Ordovician and may possibly include some Cambrian. In any case, the statement that many thousands of feet of sediments and volcanics accumulated during the Ordovician and perhaps in part during the Cambrian is correct (Fig. 18). Although fossils are lacking, many of these sediments are presumably marine. As indicated on previous pages, it is possible that the Gile Mountain, Standing Pond, and Waits River formations are Silurian and/or Devonian.

In southeastern New Hampshire the Rye formation is perhaps Ordovician, the equivalent of the Ammonoosuc volcanics. If this is correct, it is probable that a continuous sheet of sediments and volcanics was laid down at this time across all New Hampshire. Under the Merrimack synclinorium, these rocks, if not destroyed by younger intrusions, would lie far beneath the present surface of the earth.

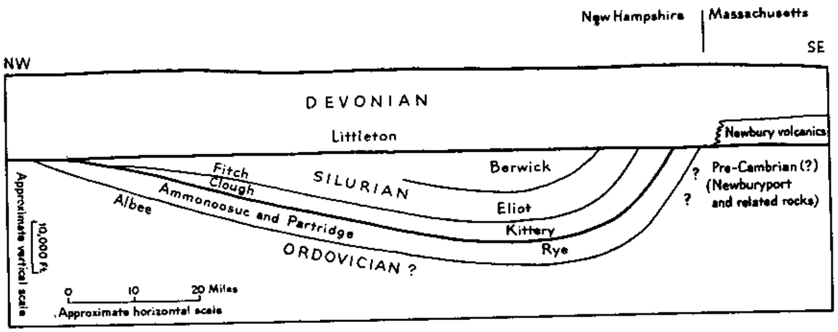

Figure 18. Stratigraphic sequence just prior to Acadian revolution.

In Late Ordovician the rocks of western New Hampshire were folded and injected by the Highlandcroft plutonic series. The effects of this orogeny extended westward into eastern New York. The eastern limits are unknown, but may lie somewhere in central New Hampshire, because around Boston some very tenuous evidence indicates that the Cambrian rocks were not deformed until after the Pennsylvanian rocks were deposited. Similarly, for what it is worth, the Rye formation in southeastern New Hampshire is conformable with the overlying Kittery quartzite.

Silurian. Erosion attacked this uplifted orogenic belt in central New Hampshire and by Early or Middle Silurian time a surface of low relief had been cut. A transgressing sea then invaded western New Hampshire in Early or Middle Silurian time. Northeast of Woodsville this sea was advancing from the southwest, because the several belts of Clough quartzite pinch out toward the northeast. This invasion towards the northeast may have been very local, the sea as a whole coming in from some other direction. Sands and gravels accumulated on the floor of the invading sea during Clough time, but these eventually gave way in middle Silurian time to calcareous sediments, such as limestone, calcareous sand, and calcareous mud. This Silurian sea

extended at least as far west as north-central Vermont and adjoining parts of Quebec.

This Silurian sea probably also extended eastward beyond the present shore of the Atlantic Ocean. Many thousands of feet of slightly calcareous silt accumulated in southeastern New Hampshire as the ancestors of the rocks of the Merrimack group. Presumably the Silurian rocks formed a continuous sheet across New Hampshire. But the more rapid subsidence of the basement in eastern New Hampshire permitted the accumulation of many thousands of feet of sediment, whereas in western New Hampshire the basement was subsiding slowly, so that only a thousand feet of sediment was deposited there (Fig. 18).

Devonian. Whether a hiatus exists between the Silurian and Devonian is not certain. In any case, deposition of large quantities of sand and mud began in the later part of the Early Devonian. Small amounts of volcanic material were erupted simultaneously with the deposition of these sands and muds. Although in much of western New Hampshire the Devonian was deposited on Silurian rocks, the Devonian sea transgressed directly onto the Ordovician (?) rocks north of the Presidential Range. Sedimentation probably ended in the early part of the Middle Devonian.

Thus during the Ordovician, Silurian and Devonian periods, 30,000 to 40,000 feet of sediments, including some volcanics, were deposited over New Hampshire. Although some of these sediments were undoubtedly reworked and redeposited after they were first laid down, it is apparent that some large source of sediments must have been available. The volcanics are an inadequate source, nor is there any evidence of islands of older rocks that could have been an important source. It is apparent that a large landmass, Appalachia, lying in what is now the Gulf of Maine, was the source.

The Acadian revolution began in New Hampshire in the Middle Devonian. The rocks were folded, faulted, regionally metamorphosed, and injected by the Oliverian and New Hampshire plutonic series at this time (Fig. 19). The sequence of events was very complex. The Oliverian series was injected as a large sheet of magma rather early in the orogeny. The Northey Hill and Monroe thrusts followed much of the folding, but were themselves involved in some of the later deformation. Much of the New Hampshire plutonic series is syntectonic. The climax of the regional metamorphism was essentially contemporaneous with the injection of the Bethlehem gneiss and Kinsman quartz monzonite. Although much of the metamorphism accompanied the deformation, some of the recrystallization followed the deformation. The Ammonoosuc thrust is younger than the regional metamorphism. The binary granites, at least in most of New Hampshire, followed the deformation, but some of the binary granites of southeastern New Hampshire have been deformed. Whether the deformation here was somewhat younger than the deformation further to the northwest or the binary granites here are somewhat older is not clear. Sediments derived from the erosion of these Acadian Mountains, including their southwestward continuation to the southeast of New Jersey, formed the great Middle and Upper Devonian delta of eastern Pennsylvania and adjacent states.

Mississippian (?). After the Acadian Mountains had been deeply eroded and the plutonic rocks of the New Hampshire plutonic series were exposed, magmas of the White Mountain series became available in the Mississippian (?). Large amounts of magma erupted on the surface of the earth to form the Moat volcanics (Fig. 20). Basalt, andesite, rhyolite and some trachyte poured out as flows and exploded into the air as pyroclastic material. Whether the surface upon which these volcanics were deposited was relatively smooth or had considerable relief is not known. Moreover, there is no direct evidence whether the Moat volcanics were largely confined to the areas occupied by the present cauldrons or covered a much larger area. Analogy with similar areas in Norway and Scotland suggests that the volcanics may have covered much of New Hampshire. Much of the magma consolidated beneath the surface of the earth to form the plutonic rocks of this series. These plutonic rocks became progressively more siliceous with the passage of time. Many ring-dikes and stocks were emplaced. When the magma attained the composition of the Albany porphyritic quartz syenite, ring fractures penetrated to the surface of the earth and large circular blocks of Moat volcanics subsided. Still later, with the subsidence of similar blocks, stocks of granite, especially the Conway granite, were emplaced. Although the Moat volcanics that are still preserved are older than many of the plutonic rocks of the White Mountain

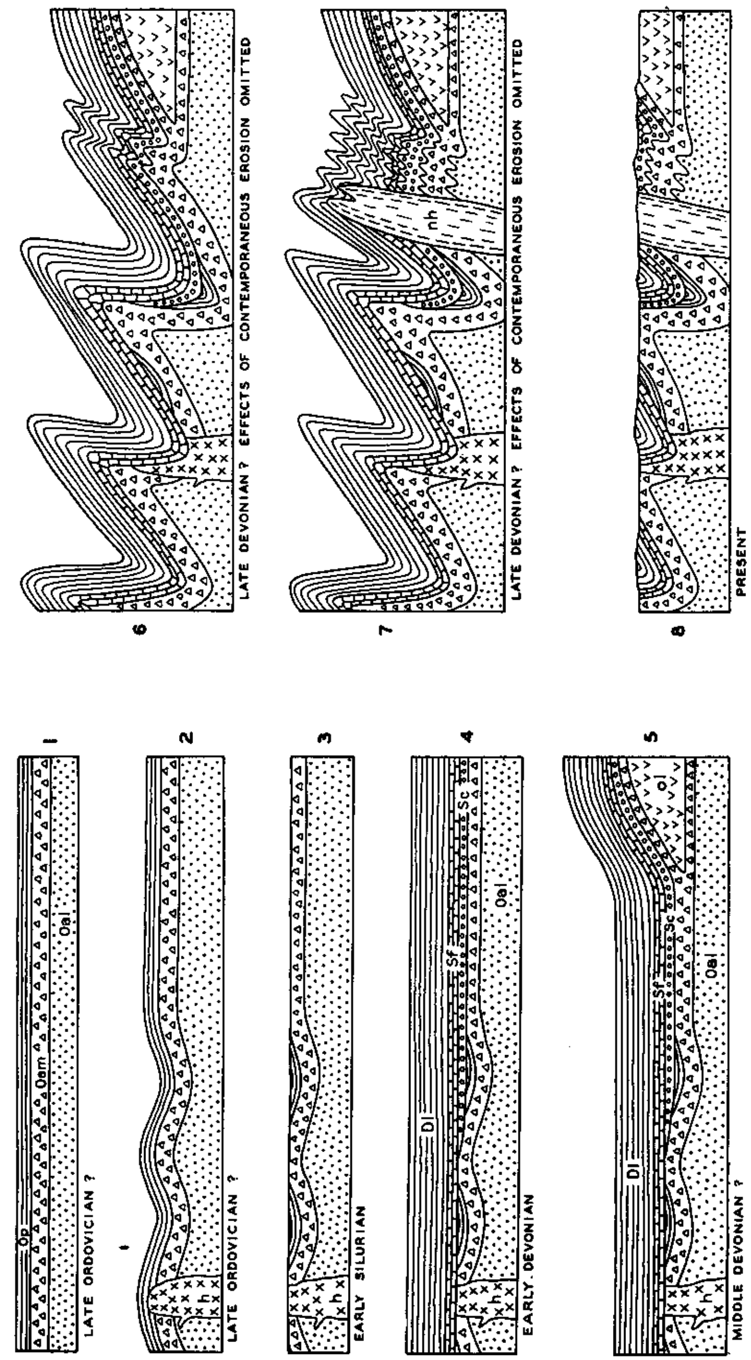

Figure 19. Diagrammatic sections illustrating geological history of western New Hampshire. *Oal* = Albee and older formations; *Oam* = Ammonoosuc volcanics; *Op* = Partridge formation; *h* = Highlandcroft plutonic series; *Sc* = Clough quartzite; Sf = Fitch formation; *Dl* = Littleton formation; *ol* = Oliverian plutonic series; *nh* = New Hampshire plutonic series.

series, surface volcanism probably continued throughout the emplacement of the syenites, quartz syenites, and granites, as evidenced by the vent agglomerate in the Belknap Mountains. Numerous dikes were associated with the White Mountain series.

Triassic. Some gravity (normal) faulting is of Triassic age. In extreme southwestern New Hampshire the fault following the Ashuelot River on the east side of the Kinsman quartz monzonite cuts the Triassic rocks in Massachusetts. By analogy, some of the other gravity faults further north in New Hampshire are also presumably Triassic.

Post-Triassic time. Throughout Jurassic, Cretaceous and Cenozoic time, erosion attacked the rocks of New Hampshire. An analysis of the erosional history of the central Appalachians and the depositional history of the Coastal Plain suggests that not less than a mile of rock has been removed from New Hampshire since Early Cretaceous time. Even more was probably eroded in earlier geological periods. The fascinating story of the later erosional history and especially the glaciation of Pleistocene time is described in Part One of this publication.

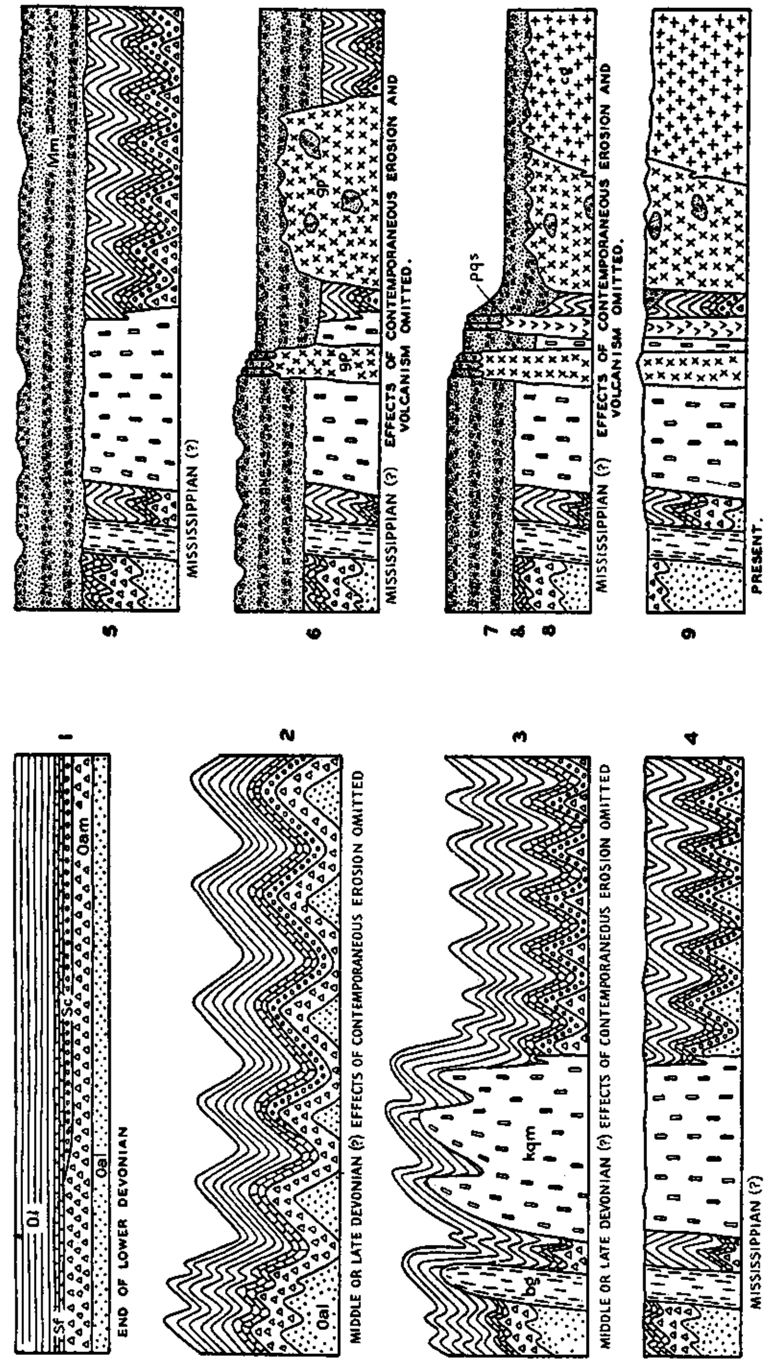

Figure 20. Diagrammatic sections illustrating geological history of central New Hampshire. *Oal* = Albee formation and older formations; *Oam* = Ammonoosuc volcanics; *Sc* = Clough quartzite; *Sf* = Fitch formation; *Dl* = Littleton formation; *bg* = Bethlehem gneiss; *kqm* = Kinsman quartz monzonite; *Mm* = Moat volcanics; *gp* = Lafayette granite porphyry; *pqs* = porphyritic quartz syenite; *cg* = Conway granite and Mt. Osceola granite.

REFERENCES

Ambrose, J. W. (1942) Preliminary map, Mansonville, Quebec: Canadian Geol. Survey, Paper 43-12.

Balk, Robert (1941) *Devonian Bernardston formation of Massachusetts restudied:* Geol. Soc. America Bull., vol. 52, p. 2009-2010 (abs.).

Bannerman, H. M. (1943) *Structural and economic features of some New Hampshire pegmatites:* N. H. Min. Resource Survey, Part VII, N. H. Planning and Development Commission.

Bean, R. J. (1953) *Relation of gravity anomalies to the geology of central Vermont and New Hampshire:* Geol. Soc. America Bull., vol. 64, p. 509-538.

Billings, M. P. (1927) *Topaz and phenacite from Baldface Mountain, Chatham, New Hampshire:* Am. Min., vol. 12, p. 173-179.

——— (1928) *The petrology of the North Conway quadrangle in the White Mountains of New Hampshire:* Proc. Am. Acad. Arts and Sci., vol. 63, p. 67-137.

——— (1929) *Structural geology of the eastern part of the Boston Basin:* Amer. Jour. Sci., 5th ser., vol. 18, p. 97-137.

——— (1934) *Paleozoic age of the rocks of central New Hampshire:* Science, vol. 79, p. 55-56.

——— (1935) *Geology of the Littleton and Moosilauke quadrangles, New Hampshire:* N. H. Planning and Development Commission, 51 pp.

——— (1937) *Regional metamorphism of the Littleton-Moosilauke area, New Hampshire:* Geol. Soc. America Bull., vol. 48, p. 463-566.

——— (1937) *Introduction of potash during regional metamorphism in western New Hampshire:* Geol. Soc. America Bull., vol. 49, p. 289-302.

——— (1941) *Structure and metamorphism in the Mount Washington area, New Hampshire:* Geol. Soc. America Bull., vol. 52, p. 863-936.

——— (1942) *Geology of the central area of the Ossipee Mountains, New Hampshire, earthquakes:* Bull. Seism Soc. Amer., vol. 32, p. 83-92.

——— (1943) *Ring-dikes and their origin:* Transactions of New York Acad. Sci., Series II, vol. 5, p. 131-144.

——— (1945) *Mechanics of igneous intrusion in New Hampshire:* Amer. Jour. Sci., vol. 243-A, p. 40-68.

——— (1948) *Orogeny in the Appalachian Highlands of New England:* Tulsa Geological Soc. Digest, vol. 16, p. 48-53.

Billings, M. P. and A. B. Cleaves (1934) *Paleontology of the Littleton area, New Hampshire:* Amer. Jour. Sci., vol. 28, 5th ser., p. 412-438.

Billings, M. P. and A. B. Cleaves (1935) *Brachiopods from mica schist, Mt. Clough, New Hampshire:* Amer. Jour Sci., vol. 30, 5th ser., p. 530-536.

Billings, M. P. and C. A. Chapman, R. W. Chapman, K. Fowler-Billings and F. B. Loomis, Jr. (1946) *Geology of the Mt. Washington quadrangle, New Hampshire:* Geol. Soc. America Bull., vol. 57, p. 261-274.

Billings, M. P. and R. P. Sharp (1937) *Petrofabric study of a fossiliferous schist, Mt. Clough, New Hampshire:* Amer. Jour. Sci., 5th ser., vol. 34, p. 277-292.

Billings, M. P. and C. R. Williams (1935) *Geology of the Franconia quadrangle, New Hampshire:* N. H. Planning and Development Commission, 35 pp.

Billings, M. P., K. Fowler-Billings, C. A. Chapman, R. W. Chapman and R. P. Goldthwait (1946) *Geology of the Mt. Washington quadrangle, New Hampshire:* N. H. Planning and Development Commission, 56 pp.

Billings, M. P. and N. B. Keevil (1946) *Petrography and radioactivity of four Paleozoic magma series in New Hampshire:* Geol. Soc. America Bull., vol. 57, p. 797-828.

Billings, M. P. and W. S. White (1950) *Metamorphosed mafic dikes of the Woodsville quadrangle, Vermont and New Hampshire:* American Mineralogist, vol. 35, p. 629-643.

Billings, M. P., J. B. Thompson and John Rodgers (1952) *Geology of the Appalachian Highlands of east-central New York, southern Vermont, and southern New Hampshire: Guidebook for Field Trips in New England,* Geol. Soc. America, p. 1-71.

Boucot, A. J. (1953) *The Lower Devonian rocks of west-central Maine:* doctoral thesis, Harvard University, 135 pp.

Cady, W. M. (1950) *Fossil cup corals from the metamorphic rocks of central Vermont:* Amer. Jour. Sci., vol. 248, p. 488-497.

Cameron, E. N. et al. (1945) *Structural and economic characteristics of New England mica deposits:* Economic Geology, vol. 40, p. 369-393.

Cameron, E. N. et al. (1954) *Pegmatite investigations, 1942-1945, New England:* U. S. Geol. Survey Professional Paper 255, 352 pp.

Chapman, C. A. (1939) *Geology of the Mascoma quadrangle, New Hampshire:* Geol. Soc. America Bull., vol. 50, p. 127-180.

——— (1942) *Intrusive domes of the Claremont-Newport area, New Hampshire:* Geol. Soc. America Bull., vol. 53, p. 889-916.

——— (1952) *Structure and petrology of the Sunapee quadrangle, New Hampshire:* Geol. Soc. America Bull., vol. 63, p. 381-425.

——— (1953) *Problem of inverted zones of metamorphism in western New Hampshire:* Illinois Acad. of Sci., Transactions, vol. 46, p. 115-123.

——— (1953) *Geology of the Sunapee quadrangle, New Hampshire:* N. H. Planning and Development Commission, 32 pp.

Chapman, C. A., M. P. Billings and R. W. Chapman (1944) *Petrology and structure of the Oliverian magma series in the Mount Washington quadrangle, New Hampshire:* Geol. Soc. America Bull., vol. 55, p. 497-516.

Chapman, R. W. (1935) *Percy ring-dike complex:* Amer. Jour. Sci., 5th ser., vol. 30, p. 401-431.

——— (1937) *Petrology of the syenite stock at Cherry Mountain, New Hampshire:* Amer. Jour. Sci., 5th ser., vol. 33, p. 174-186.

——— (1949) *The geology of the Percy quadrangle, New Hampshire:* N. H. Planning and Development Commission, 38 pp.

——— (1942) *Ring structures of the Pliny region, New Hampshire:* Geol. Soc. America Bull., vol. 53, p. 1533-1568.

——— (1948) *Petrology and structure of the Percy quadr gle, New Hampshire:* Geol. Soc. American Bull., vol. 59 1059-1100.

Chapman, R. W. and C. R. Williams (1935) *Evolution of White Mountain magma series:* American Mineralogist, 20, p. 502-530.

Chayes, F. (1950) *Composition of some New England grani* Transactions New York Acad. of Sci., Ser. 2, vol. 12, p. 1 151.

——— (1952) *The finer-grained calcalkaline granites of N England:* Jour. of Geol., vol. 60, p. 207-254.

Chidester, A. H., M. P. Billings and W. M. Cady, *Talc investi tions in Vermont*: preliminary report, U. S. Geological S vey, Circular 95, 1951.

Clark, T. H. (1934) *Structure and stratigraphy of South Quebec:* Geol. Soc. America Bull., vol. 45, p. 1-20.

——— (1936) *Silurian rocks of Lake Memphremagog, Q bec:* The Canadian Field-Naturalist, vol. 50, p. 31-33.

Cooke, H. C. (1950) *Geology of a southwestern part of the e ern townships of Quebec:* Geological Survey of Can Memoir 257, 142 pp.

Cooper, G. A. et al. (1942) *Correlation of the Devonian sedin tary formations of North America:* Geol. Soc. America B vol. 53, p. 1729-1794.

Currier, L. W. and R. H. Jahns (1941) *Ordovician stratigra of central Vermont:* Geol. Soc. America Bull., vol. 52, p. 1 1512.

Dale, T. N. (1923) *The commercial granites of New Englo* U. S. Geol. Survey, Bull. 738.

Daly, R. A. (1897) *Studies on the so-called porphyritic gneis New Hampshire:* Jour. of Geol., vol. 5, p. 694-722, 766-79

——— (1903) *The Geology of Ascutney Mountain, Verm* U. S. Geol. Survey, Bull. 209, 122 pp.

Doll, C. G. (1943a) *A Paleozoic revision in Vermont:* Amer. J Sci., vol. 241, p. 57-64.

——— (1943b) *A brachiopod from mica schist, South St ford, Vermont:* Amer. Jour. Sci., vol. 241, p. 676-679.

——— (1944) *A preliminary report on the geology of the Strafford quadrangle, Vermont:* Report of the State Geologist, Vermont, 1943-1944, 24th of this series, p. 14-28.

——— (1951) *Geology of the Memphremagog quadrangle and the southeastern portion of the Irasburg quadrangle, Vermont:* Vermont Geol. Survey, Bull. No. 3, 113 pp.

Dowse, Alice N. (1950) *New Evidence on the Cambrian contact at Hoppin Hill, North Attleboro, Massachusetts:* Amer. Jour. Sci., vol. 248, p. 95-99.

Dresser, J. A., and T. C. Denis (1949) *Geology of Quebec:* vol. II, Descriptive Geology, Geol. Report 20, Department of Mines, Quebec.

Emerson, B. K. (1898) *Geology of old Hampshire County, Massachusetts:* U. S. Geol. Survey, Monograph 29, p. 253-299.

——— (1917) *Geology of Massachusetts and Rhode Island:* U. S. Geological Survey, Bull. 597, 289 pp.

Eric, J. H. (1942) *Geology of the Vermont portion of the Littleton quadrangle, Vermont-New Hampshire:* doctoral thesis, Harvard University.

Eskola, P. E. (1949) *The problem of mantled gneiss domes:* Quarterly Journal, Geol. Soc. of London, vol. 104, p. 461-476.

Faul, Henry (1954) *Nuclear geology:* New York, 414 pp.

Fenneman, N. M. (1931) *Physiography of western United States:* New York, 543 pp.

——— (1938) *Physiography of eastern United States:* New York, 714 pp.

Fisher, I. S. (1952) *Geology of the Bethel area, Maine:* doctoral thesis, Harvard University, 146 pp.

Fisher, L. W. (1941) *Structure and metamorphism of Lewiston, Maine, region:* Geol. Soc. America Bull., vol. 52, p. 107-160.

Foerste, A. F. (1920) *Presence of Upper Silurian sandstone in Essex County, northeastern Massachusetts:* Geo. Soc. America Bull., vol. 31, p. 206-207.

Fowler-Billings, Katharine (1942) *Geologic map of the Cardigan quadrangle, New Hampshire:* Geol. Soc. America, Bull., vol. 53, p. 177-178.

——— (1944) *Sillimanite deposits in the Monadnock quadrangle, New Hampshire:* Mineral Resource Survey, Part 8, N. H. Planning and Development Commission, 15 pp.

——— (1944) *Igneous and metasedimentary dikes of the Mt. Washington area, New Hampshire:* Geol. Soc. America Bull., vol. 56, p. 1255-1278.

——— (1949) *Geology of the Monadnock quadrangle, New Hampshire:* N. H. Planning and Development Commission, 43 pp.

——— (1949) *Geology of the Monadnock region of New Hampshire:* Geol. Soc. America Bull., vol. 60, p. 1249-1280.

Fowler-Billings, K. and L. R. Page (1942) *Geology of the Cardigan and Rumney quadrangles, New Hampshire:* N. H. Planning and Development Commission, 31 pp.

Fowler-Lunn, K. and L. Kingsley (1937) *Geology of the Cardigan quadrangle, New Hampshire:* Geol. Soc. America Bull., vol. 48, p. 1363-1386.

Freedman, Jacob (1950) *Geology of the Mt. Pawtuckaway quadrangle, New Hampshire:* N. H. Planning and Development Commission, 34 pp.

——— (1950) *Stratigraphy and structure of the Mt. Pawtuckaway quadrangle, southeastern New Hampshire:* Geol. Soc. America Bull., vol. 61, p. 449-492.

Gillson, J. L. (1927) *The Granite of Conway, New Hampshire, and its druse minerals:* American Mineralogist, vol. 12, p. 307-319.

Goldthwait, J. W. (1925) *The geology of New Hampshire:* New Hampshire Acad. of Sci. Handbook No. 1, 86 pp., Concord, N. H.

Goldthwait, J. W., L. Goldthwait, and R. P. Goldthwait (1951) *The geology of New Hampshire:* Part I, Surficial Geology, New Hampshire State Planning and Development Commission, 83 pp.

Grabau, A. W. et al (1898) *Guide to localities illustrating the geology of the vicinity of Boston:* Amer. Assoc. Advancement of Sci., 50th Anniversary meeting, Boston.

Hadley, J. B. (1942) *Stratigraphy, structure, and petrology of the Mt. Cube area, New Hampshire:* Geol. Soc. America Bull., vol. 53, p. 113-176.

——— (1949) *Bedrock geology, Mount Grace quadrangle, Massachusetts:* Geol. Quad. maps of the United States, U. S. Geol. Survey.

——— (1950) *Geology of the Bradford-Thetford area, Orange County, Vermont:* Bull. No. 1, Vermont Geol. Survey, 36 pp.

Hadley, J. B. and C. A. Chapman (1939) *Geology of Mt. Cube and Mascoma quadrangles, New Hampshire:* N. H. Planning and Development Commission, 28 pp.

Hawes, G. W. (1879) *On a group of dissimilar eruptive rocks in Campton, New Hampshire:* Amer. Jour. Sci., 3rd ser. vol 17, p. 147-151.

——— (1881) *The Albany granite, New Hampshire, and its contact phenomena:* Amer. Jour. Sci., 3rd ser., vol 21, p. 21-32.

Heald, M. T. (1950) *The geology of the Lovewell Mountain quadrangle, New Hampshire:* N. H. Planning and Development Commission, 29 pp.

——— (1950) *Structure and petrology of the Lovewell Mountain quadrangle, New Hampshire:* Geol. Soc. America Bull., vol 61, p. 43-89.

Henderson, D. M. (1949) *Geology and petrology of the eastern part of the Crawford Notch quadrangle, New Hampshire:* doctoral thesis, Harvard University, 153 pp.

——— (1950) *Metamorphic development of the eastern part of the Crawford Notch quadrangle, New Hampshire:* Trans., Illinois Acad. Sci., vol. 43, p. 165-170.

Hitchcock, C. H. (1871) *Helderberg corals in New Hampshire:* Amer. Jour. Sci., 3rd ser., vol. 2, 148-149.

——— (1874) *On Helderberg corals in New Hampshire:* Amer. Jour. Sci., 3rd ser., vol. 7, p. 468-476, 557-571.

——— (1874-1878) *The geology of New Hampshire:* Vol. I, 1874; Vol. II, 1877; Vol. III, 1878, Atlas, 1878; Concord, New Hampshire.

——— (1878) *The geology of the Ammonoosuc mining district:* Concord, New Hampshire, 121 pp.

——— (1908) *Geology of the Hanover, New Hampshire, quadrangle:* Vermont State Geologist, Report No. 6, p. 139-186.

Hitchcock, E., E. Hitchcock, Jr., A. D. Hager and C. H. Hitchcock (1861) *Geology of Vermont*, 2 vols., 988 pp.

Holmes, A. (1947) *The construction of a geological time-scale:* Transactions of the Geological Society of Glasgow, vol. 21, p. 117-152.

Jahns, R. H. (1941) *Stratigraphy of the Lowell-Fitchburg area, Massachusetts:* Geol. Soc. America Bull., vol. 52, p. 1910-1911 (abst.).

——— (1952) *Stratigraphy and sequence of igneous rocks in the Lowell-Ayer region, Massachusetts:* Guidebook for Field Trips in New England, Geol. Soc. America, p. 108-112.

Johannsen, Albert (1931-1938) *A descriptive petrography of the igneous rocks:* 4 vols., Chicago.

Johnson, Ruth H. (1935) *The petrology of the Exeter granodiorite:* Master's thesis, University of New Hampshire.

Kaiser, E. P. (1938) *Geology of the Lebanon granite, New Hampshire:* Amer. Jour. Sci., vol. 36, 5th ser., p. 107-136.

Katz, F. J. (1917) *Stratigraphy in southwestern Maine and southeastern New Hampshire:* U. S. Geol. Survey, Prof. Paper 108, Shorter Contributions to General Geology, p. 165-177.

Keeler, Jane and Charlotte Brainard (1940) *Faulted phyllites east of Greenfield, Massachusetts:* Amer. Jour. Sci., vol. 238, p. 354-365.

Kingsley, Louise (1931) *Cauldron subsidence of the Ossipee Mountains:* Amer. Jour. Sci., 5th ser., vol. 22, p. 139-168.

Knox, A. S. (1944) *A Carboniferous flora from the Wamsutta formation of southeastern Massachusetts:* Amer. Jour. Sci., vol. 242, p. 130-138.

Kruger, F. C. (1946) *Structure and metamorphism of the Bellows Falls quadrangle of New Hampshire-Vermont:* Geol. Soc. Amer. Bull., vol. 57, p. 161-206.

——— (1946) *Geology of the Bellows Falls quadrangle, New Hampshire and Vermont:* N. H. Planning and Development Commission, 19 pp.

Lahee, F. H. (1912) *A new fossiliferous horizon on Blueberry Mountain in Littleton, New Hampshire:* Science, vol. 36, p. 275-276.

——— (1913) *Geology of the new fossiliferous horizon and underlying rocks in Littleton, New Hampshire:* Amer. Jour. Sci., 4th ser., vol. 36, p. 231-250.

——— (1916) *Origin of the Lyman schists of New Hampshire:* Jour. of Geol., vol. 24, p. 366-381.

Lord, E. C. E. (1898) *On the dikes in the vicinity of Portland, Maine:* Am. Geol., vol. 22, p. 335-346.

Lyons, J. B. (1955) *Geology of the Hanover quadrangle, New Hampshire-Vermont:* Geol. Soc. America Bull., vol. 66, p. 105-146.

Merritt, J. W. (1913) *Structural and metamorphic geology of the Hanover district of New Hampshire:* Report of the Vermont State Geologist, 12th Annual Report, p. 1-36.

Modell, David (1936) *Ring-dike complex of the Belknap Mountains, New Hampshire:* Geol. Soc. America Bull., vol. 47, p. 1885-1932.

Moke, C. B. (1946) *Geology of the Plymouth quadrangle, New Hampshire:* N. H. Planning and Development Commission, 21 pp.

——— (1949) *Geology of the Plymouth quadrangle, New Hampshire:* doctoral thesis, Harvard University.

Moore, G. E., Jr. (1949) *Geology of the Keene-Brattleboro quadrangle, New Hampshire and Vermont:* N. H. Planning and Development Commission, 31 pp.

——— (1949) *Structure and metamorphism of the Keene-Brattleboro area, New Hampshire-Vermont:* Geol. Soc. Amer. Bull., vol. 60, p. 1613-1670.

Olson, J. C. (1950) *Feldspar and associated pegmatite minerals in New Hampshire:* N. H. Planning and Development Commission, Part XIV, Mineral Resource Survey, 50 pp.

——— (1942) *Mica-bearing pegmatites of New Hampshire:* U. S. Geol. Survey, Bull. 931, p. 363-403.

Perkins, E. H. and E. S. C. Smith (1925) *Contributions to the geology of Maine, Number 1, A geological section from the Kennebec River to Penobscot Bay:* Amer. Jour. Sci., 5th ser., vol. 9, pp. 204-228.

Perry, J. H. (1903) *Notes on the geology of Mt. Kearsarge, New Hampshire:* Jour. Geol., vol. 11, p. 403-412.

——— (1904) *Geology of Monadnock Mountain, New Hampshire:* Jour. Geol., vol. 12, p. 1-14.

——— and B. K. Emerson (1903) *The geology of Worcester, Massachusetts:* Worcester Natural History Society, 166 pp.

Pirsson, L. V. (1911) *Contributions to the geology of New Hampshire, V, Petrography of Tripyramid Mountain:* Amer. Jour. Sci., 4th ser., vol. 31, p. 405-431.

Pirsson, L. V. and H. S. Washington (1906-1907) *Contributions to the geology of New Hampshire, I, Geology of the Belknap Mountains; II, Petrography of the Belknap Mountains:* Amer. Jour. Sci., 4th ser., vol. 20, p. 344-352; 4th ser., vol. 22, p. 439-457, 593-514.

——— (1907) *Contributions to the geology of New Hampshire, III, On Red Hill, Moultonboro:* Amer. Jour. Sci., 4th ser., vol. 23, p. 257-276, 433-447.

Pirsson, L. V. and W. N. Rice (1911) *Contributions to the geology of New Hampshire, IV, Geology of Tripyramid Mountain:* Amer. Jour. Sci., 4th ser., vol. 31, p. 269-291.

Quinn, Alonzo (1937) *Petrology of the alkaline rocks at Red Hill, New Hampshire:* Geol. Soc. America Bull., vol. 48, p. 373-402.

——— (1941) *Geology of Winnipesaukee quadrangle, New Hampshire:* N. H. Planning and Development Commission. 22 pp.

——— (1944) *Magmatic contrasts in the Winnipesaukee region, New Hampshire:* Geol. Soc. America Bull., vol. 55, p. 473-496.

——— (1953) *Geology of the Wolfeboro quadrangle, New Hampshire:* N. H. Planning and Development Commission, 24 pp.

Quinn, Alonzo and G. W. Stewart (1941) *Igneous rocks of the Merrymeeting Lake area of New Hampshire:* American Mineralogist, vol. 26, p. 633-645.

Richardson, C. H. (1906) *The areal and economic geology of northeastern Vermont:* Fifth Annual Report Vermont State Geologist, p. 63-115.

Rosenbusch, H. (1886) *Physiographie der massigen Gesteine:* vol. I.

Roy, C. J. and Jacob Freedman (1944) *Petrology of the Pawtuckaway Mountains, New Hampshire:* Geol. Soc. America Bull.. vol. 55, p. 905-920.

Schuchert, Charles and C. R. Longwell (1932) *Paleozoic deformations of the Hudson Valley region:* Amer. Jour. Sci., 5th ser.. vol. 23, p. 305-326.

Smith, Althea P. (1940) *Petrogenesis and structure in the Mt. Chocorua area, New Hampshire:* doctoral thesis, Radcliffe College, 269 pp.

Smith, Althea P., Louise Kingsley and Alonzo Quinn (1939) *Geology of Mt. Chocorua quadrangle, New Hampshire:* N. H. Planning and Development Commission, 24 pp.

Sriramadas, Aluru (1955) *Geology of the Manchester quadrangle, New Hampshire: doctoral thesis,* Harvard University.

Thompson, J. B., Jr., (1954) *Structural geology of the Skitchewaug Mountain area, Claremont quadrangle, Vermont-New Hampshire:* Guidebook Forty-sixth New England Intercollegiate Geological Conference (Dartmouth College).

Thompson, J. B., Jr. (1955) *The thermodynamic basis for the mineral facies concept:* Amer. Jour. Sci., vol. 253, p. 65-103.

Turner, F. J. and J. Verhoogen (1951) *Igneous and metaphorphic petrology:* New York, 602 pp.

Wandke, Alfred (1922) *Intrusive rocks of the Portsmouth Basin, Maine and New Hampshire:* Amer. Jour. Sci., 5th ser., vol. 4, p. 139-158.

White, David (1912) *Age of the Worcester phyllite:* Washington Acad. Sci., Journal, vol. 2, p. 112-118.

White, W. S. and R. H. Jahns (1950) *Structure of central and east-central Vermont:* Jour. Geol., vol. 58, p. 179-220.

White, W. S. and M. P. Billings (1951) *Geology of the Woodsville quadrangle, Vermont-New Hampshire:* Geol. Soc. America Bull., vol. 62, p. 647-696.

Whitfield, R. P. (1883) *Observations on the fossils of the metamorphic rocks of Bernardston, Mass.:* Amer. Jour. Sc., 3rd ser., vol. 25, p. 368-369.

Williams, C. R. and M. P. Billings (1938) *Petrology and structure of the Franconia quadrangle, New Hampshire:* Geol. Soc. America Bull., vol. 49, p. 1011-1044.

Wilmarth, M. G. (1938) *Lexicon of geologic names of the United States:* Bull. 896, U. S. Geol. Survey, 2396 pages.

TABLES

TABLE 1

REPRESENTATIVE ESTIMATED MODES, ORFORDVILLE FORMATION

Minerals	Chlorite Zone			Biotite Zone				Garnet Zone							Staurolite Zone					Metasomatized Zone		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Quartz	59	20	88	50	35	50	90	60	28	83	42	43	38	20	50	40	50	tr	21	40	75	31
Potash feldspar											10	10								15		
Plagioclase	10	35		20	51	25			25		42	35	53	30	10	15	10	28	30	25		30
Sericite	20																					
Chlorite	11	15	10	10	5	15		10					tr	5	5		.5	tr	3	tr		2
Muscovite		10		15	5	5	9	15	19	5	3	11	6		10	18	15			3	8	2
Biotite				5	2	tr	1	10	24		3	1	3	2	15	20	10	tr	5	10	tr	12
Garnet								5			tr	tr	tr		2	2	7		1	tr		2
Staurolite															5	4						
Kyanite																					15	
Hornblende														26				72	33	tr		8
Epidote		tr				4					tr	tr	tr	17			2	tr	4	6		9
Calcite		20		tr		tr		tr			tr	tr	tr				tr	tr	3	tr		3
Accessories		tr	2	tr	2	1	tr	tr	4	12	tr	tr	tr	tr	3	1	1	tr		1	2	1
Average percent of anorthite in plagioclase	10	9		8	7	8			40		5	25	30	9	28	35	35	50	35	18		35

Chlorite Zone

1. Slate, northwest of Piermont (Billings, unpublished).
2. Post Pond volcanic member, chlorite schist, Hanover quadrangle (Lyons, 1955, p. 115).
3. Hardy Hill quartzite, northwest of Piermont (Billings, unpublished).

Biotite Zone

4. Phyllite, Hanover quadrangle (Lyons, 1955, p. 115).
5. Post Pond volcanic member, quartz-feldspar schist, Hanover quadrangle (Lyons, 1955, p. 115).
6. Post Pond volcanic member, chlorite schist, Hanover quadrangle (Lyons, 1955, p. 115).
7. Hardy Hill quartzite, Hanover quadrangle (Lyons. 1955, p. 115).

Garnet Zone

8. Garnet-mica schist, Hanover quadrangle (Lyons, 1955, p. 115).
9. Mica schist, calculated from chemical analysis, Mt. Cube quadrangle (Hadley, 1942, p. 118).
10. Black graphitic quartzite; accessories include 12% graphite, Mt. Cube quadrangle (Hadley, 1942, p. 118).
11. Post Pond volcanic member, fine-grained biotite gneiss (soda rhyolite) average of 2 specimens, Mt. Cube quadrangle (Hadley, 1942, p. 118).
12. Post Pond volcanic member, fine-grained biotite gneiss (quartz latite), average of 6 specimens, Mt. Cube quadrangle (Hadley, 1942, p. 118).
13. Post Pond volcanic member, fine-grained biotite gneiss (dacite) average of 3 specimens, Mt. Cube quadrangle (Hadley, 1942, p. 118).
14. Post Pond volcanic member, epidote amphibolite, average of 2 modes, Hanover quadrangle (Lyons, 1955, p. 115).

Staurolite Zone

15. Staurolite schist, Hanover quadrangle (Lyons, 1955, p. 115).
16. Staurolite schist, calculated from chemical analyis, Mt. Cube quadrangle (Hadley, 1942, p. 118).
17. Garnet schist, Hanover quadrangle (Lyons, 1955, p. 115).
18. Amphibolite, average of 7 specimens, Mt. Cube quadrangle (Hadley, 1942, p. 118).
19. Hornblende schist, average of 2 modes, Hanover quadrangle (Lyons, 1955, p. 115).

Metasomatized Zone around Lebanon granite

20. Biotite gneiss, Hanover quadrangle (Lyons, 1955, p. 115).
21. Kyanite schist, Hanover quadrangle (Lyons, 1955, p. 115).
22. Hornblende-biotite gneiss, Hanover quadrangle (Lyons, 1955, p. 115).

TABLE 2

REPRESENTATIVE ESTIMATED MODES, ALBEE FORMATION

Minerals	Chlorite Zone					Staurolite Zone						Sillimanite Zone
	1	2	3	4	5	6	7	8	9	10	11	12
Quartz	37	34	70	82	63	37	39	40	72	86	84	45
Potash Feldspar												
Plagioclase	5		2		23	4		25	5		5	9
Sericite	30	52	19	13	7							
Muscovite						28	30	10	10	6	3	22
Chlorite	25	10	9	5	6		tr	3	7		1	1
Biotite						21	21	17	2	8	5	18
Garnet						8	2		tr		1	tr
Staurolite							6	5				tr
Sillimanite												3
Accessories	3	4	tr		1	2	2	tr	4		1	2
Average percent of anorthite in plagioclase	5		5		10	20		40	30		20	27

Chlorite Zone

1. Black slate, Littleton-Moosilauke area (Billings, 1937, p. 473).
2. Green slate, Littleton-Moosilauke area, average 2 sections (Billings, 1937, p. 473).
3. Argillaceous quartzite, Littleton-Moosilauke area, average 3 sections (Billings, 1937, p. 473).
4. Quartzite, Littleton-Moosilauke area, average 3 sections (Billings, 1937, p. 473).
5. Feldspathic quartzite, Littleton-Moosilauke area, average 4 sections (White and Billings, 1951, p. 659).

Staurolite Zone

6. Biotite-garnet schist, Littleton-Moosilauke area, average 4 sections (Billings, 1937, p. 473).
7. Staurolite-garnet-mica schist, Piermont member, average 2 sections (White and B.llings, 1951, p. 659).
8. Feldspar-staurolite-mica schist, Piermont member (White and Billings, 1951, p. 659).
9. Mica-quartz schist, Woodsville area, average 2 sections (White and Billings, 1951, p. 659).
10. Micaceous quartzite, Littleton-Moosilauke area (Billings, 1937, p. 473).
11. Quartzite, Woodsville area (White and Billings, 1951, p. 659).

Sillimanite Zone

12. Sillimanite schist, Woodsville area, average 3 sections (White and Billings, 1951, p. 659).

TABLE 3

REPRESENTATIVE ESTIMATED MODES, AMMONOOSUC VOLCANICS

Minerals	Chlorite Zone					Staurolite and Sillimanite Zones												
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Quartz	35	6	15	37	66	37	29	40	40	37	2	5	3	1	2	22	90	45
Potash feldspar	12					46	20	20		3						tr		
Plagioclase	34	35	28	7	5	10	40	33	56	44	42	28	27	44	39	62		12
Sericite	10	6	2	40	14											tr	1	
Muscovite						2	tr			3								15
Chlorite	7	31	31	15	12		tr		3		2	2		1	tr	1	1	
Epidote		9	21	1	2		1	tr	tr	tr	4			2				
Biotite						5	10	6	1	13	4	tr		tr		1	1	25
Hornblende								1	tr		45	64	68	51	58	13*		
Garnet									tr									3
Sillimanite																	8	tr
Calcite	2	11									tr							
Accessories		2	3		1	tr	tr	tr	tr	tr	1	1	2	1	1	1	tr	
Average percent of anorthite in plagioclase	10	10	10	10	10	10	35	35	23	32	40	60	45	60	30	26		15

* Actinolite

Chlorite Zone

1. Soda rhyolite, calculated from chemical analyses, Littleton-Moosilauke area (Billings, 1937, Table 3).
2. Chlorite schist, average of 9 specimens, Littleton-Moosilauke area (Billings, 1937, Table 3).
3. Chlorite-epidote schist, Littleton-Moosilauke area (Billings, 1937, Table 3).
4. Slate, Littleton-Moosilauke area (Billings, 1937, Table 3).
5. Impure quartzite, average of 4 specimens, Littleton-Moosilauke area (Billings, 1937, Table 3).

Staurolite and Sillimanite Zones

6. Fine-grained biotite gneiss (metarhyolite), calculated from chemical analysis, Mt. Washington area (Billings, 1941, p. 874).
7. Fine-grained biotite gneiss (metamorphosed quartz latite), average of 3 specimens, Mt. Cube area (Hadley, 1942, p. 128).
8. Fine-grained biotite gneiss (metamorphosed quartz latite), Mt. Washington area (Billings, 1941, p. 874).
9. Fine-grained biotite gneiss (metadacite), average of 5 specimens, Mt. Cube area (Hadley, 1942, p. 128).
10. Fine-grained biotite gneiss (metadacite), average of 2 specimens, Mt. Washington area (Billings, 1941, p. 874).
11. Amphibolite, average of 11 specimens, Littleton-Moosilauke area (Billings, 1937, Table 3).
12. Amphibolite, average of 3 specimens, Mt. Cube area (Hadley, 1942, p. 128).
13. Amphibolite, average of 2 specimens, Mt. Washington area (Billings, 1941, p. 874).
14. Amphibolite, average of 6 specimens, Mascoma quadrangle, (C. A. Chapman, 1939, p. 136).
15. Amphibolite, average of 5 specimens, Keene quadrangle, Moore, 1949, p. 1624).
16. Actinolite-quartz-feldspar gneiss, average of 2 specimens, Keene quadrangle (Moore, 1949, p. 1624).
17. Sillimanite quartzite, Keene quandrangle (Moore, 1949, p. 1624).
18. Mica schist, Mt. Washington area (Billings, 1941, p. 874).

TABLE 4

REPRESENTATIVE ESTIMATED MODES, FITCH FORMATION

Minerals	Chlorite Zone								Staurolite Zone								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Quartz ...	2	6	33	21	36	54	42	45	4	56		6	36	30	35	98	64
Potash feldspar ..			7	4		tr		46		10	10						
Plagioclase			11		tr	4	5	4		7	10	10	26	33			
Sericite ..	1	3	22	47	3	7	25	4									
Chlorite ..	tr		11	14			17		tr						2		
Muscovite									2						2	2	10
Biotite ...									3			1	8	20	1	1	15
Calcite ...	94	88		12	60	35			90	4	3	32	10	15	60		4
Dolomite .		2	16														
Ankerite ..							2										
Actinolite .										4	10	49	27				
Diopside ..										19	60						
Sphene ...											2	2	2				
Accessories	3	1	tr	2	1		9	1	1		5		1	2	tr	tr	7
Average percent anorthite in plagioclase			10			10	10	10		60	60	60	60	60			

Chlorite Zone

1. Bluish-gray limestone, average 3 specimens.
2. White marble, average 2 specimens.
3. Slaty dolomite, calculated from chemical analysis.
4. Calcareous slate, average 2 specimens.
5. Arenaceous limestone.
6. Calcareous sandstone.
7. Slate.
8. Arkose, average of 3 specimens.

Staurolite Zone

9. Marble, average 3 specimens.
10. Quartz-diopside-actinolite granulite, average 2 specimens.
11. Diopside-actinolite granulite.
12. Actinolite marble and actinolite-calcite schist, average 2 specimens.
13. Biotite-actinolite schist.
14. Biotite-calcite schist.
15. Arenaceous marble.
16. Quartzite.
17. Mica schist.

All specimens are from Littleton-Moosilauke area (Billings, 1937, Table 5)

TABLE 5
REPRESENTATIVE ESTIMATED MODES, METASEDIMENTARY ROCKS OF THE LITTLETON FORMATION

Minerals	Chlorite Zone				Staurolite Zone										Sillimanite Zone														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Quartz	31	75	85	90	43	44	44	50	25	72	85	84	5	58	30	45	50	48	66	87	38	41	40		11	21	23	27	40
Potash feldspar ...														tr		tr						8		9	22	16		13	3
Plagioclase	11											8	35	20	1	2	2		3	3	14	5		19	10	31	13	25	10
Sericite	32	13	9	5											7	6				tr									
Muscovite					30	24	29	22	30	9		2		1	33	25	6	20	16	2	21		35					1	
Chlorite	25	7	3	2								1			5	3			1	tr	2		10						
Biotite					20	12	19	14	20	11	11	3		1	19	15	25	20	14	8	23	25	6	1	4	1	26	32	32
Garnet					tr	15	4	5	5	3	2	2		9	2	1	3	4	tr	tr		7							5
Staurolite								3	20			tr			tr	tr			tr										
Sillimanite															3	3	12		tr	tr	1	12	1						
Cordierite																						2							
Andalusite																		8											
Actinolite													60	4										tr	23	29	34		
Diopside														6										69	29				
Pyrite	tr				3	3	1	1		1										tr	1	tr	2	tr		tr	2	1	10
Opaque oxides		2			2		1	2	tr	3	2	tr			tr	tr	2		tr	tr	tr	tr	1						
Sphene													tr	tr									tr	2	1	2	2	tr	tr
Miscellaneous	1	3	3	3	2	2	2	3	tr	1	tr	tr	tr	1						tr	tr	tr	5			tr		1	tr
Average percentage of anorthite in plagioclase	10											22	25	83	20	22	?		15	12	20	28	16	70	82	53	77	34	92

Chlorite Zone
1. Slate, Littleton-Moosilauke area, calculated from chemical analysis (Billings, 1937, p. 488).
2. Arenaceous slate, Littleton-Moosilauke area, average of 3 specimens (Billings, 1937, p. 488).
3. Argillaceous sandstone, Littleton-Moosilauke area, average of 6 specimens (Billings, 1937, p. 488).
4. Sandstone, Littleton-Moosilauke area (Billings, 1937, p. 488).

Staurolite Zone
5. Biotite schist, Littleton-Moosilauke area, average of 2 specimens (Billings, 1937, p. 488).
6. Garnet-biotite schist, Littleton-Moosilauke area (Billings, 1937, p. 488).
7. Biotite-garnet schist, Littleton-Moosilauke area, average of 2 specimens (Billings, 1937, p. 488).
8. Biotite-garnet-staurolite schist, Littleton-Moosilauke area, average of 3 specimens (Billings, 1937, p. 488).
9. Staurolite-mica-garnet schist, Keene-Brattleboro area (Moore, 1949, p. 1630).
10. Mica-quartz schist, Littleton-Moosilauke area, average of 4 specimens (Billings, 1937, p. 488).
11. Quartz-mica schist, Littleton-Moosilauke area, average of 2 specimens (Billings, 1937, p. 488).
12. Quartzite, Keene-Brattleboro area (Moore, 1949, p. 1630).
13. Actinolite-oligoclase schist, Keene-Brattleboro area (Moore, 1949, p. 1630).
14. Bytownite-garnet-diopside granulite, Keene-Brattleboro area (Moore, 1949, p. 1630).

Sillimanite Zone
15. Coarse sillimanite schist, Mt. Washington area, average of 7 specimens (Billings, 1941, p. 894).
16. Sillimanite schist, Mt. Washington area, average of 7 specimens, (Billings, 1941, p. 894).
17. Sillimanite schist, Mt. Monadnock quadrangle, average of 2 specimens (K. Fowler-Billings, 1949, p. 1259).
18. Andalusite schist, Mt. Washington area (Billings, 1941, p. 894).
19. Mica-quartz schist, Mt. Washington area, average of 4 specimens (Billings, 1941, p. 894).
20. Quartzite, Mr. Washington area, average of 5 specimens (Billings, 1941, p. 894).
21. Gneiss, Gorham quadrangle, average of 4 modes calculated from chemical analysis (M. P. Billings and K. Fowler-Billings, unpublished).
22. Gneiss with orthoclase porphyroblasts, Lovewell Mountain quadrangle, calculated from chemical analysis (Heald, 1950, p. 52).
23. Pyritiferous muscovite gneiss, Lovewell Mountain quadrangle, calculated from chemical analysis (Heald, 1950, p. 52).
24. Diopside granulite, Boott member, Mt. Washington area, average of 2 specimens (Billings, 1941, p. 883).
25. Diopside-actinolite granulite, Boott member, Mt. Washington area, average of 8 specimens (Billings, 1941, p. 883).
26. Actinolite granulite, Boott member, Mt. Washington area, average of 4 specimens (Billings, 1941, p. 883).
27. Actinolite-biotite granulite, Boott member, Mt. Washington area, average of 3 specimens (Billings, 1941, p. 883).
28. Biotite schist, Boott member, Mt. Washington area, average of 7 specimens (Billings, 1941, p. 883).
29. Biotite-pyrite schist, Boott member, Mt. Washington area, 1 specimen (Billings, 1941, p. 883).

TABLE 6

APPROXIMATE AVERAGE MODES, HIGHLANDCROFT PLUTONIC SERIES

Minerals	1	2	3	4	5	6	7
Quartz	1		30	23	15	29	23
Potash feldspar †					22	29	60
Plagioclase	50	50	45	35	25	19	13
Amphibole *	20	40		3	8		
Biotite		8		24	7	10	4
Sericite			10		10	7	4
Opaque oxides	2		2		tr	tr	
Epidote ‡	25		4	10	8	5	3
Chlorite			7		2		
Calcite	2		2		3		tr
Miscellaneous		2		4	tr	1	3
Percent of anorthite in plagioclase	10	35	10	35	10	10	5

† Potash feldspar is orthclase and microcline.

* Amphibole is hornblende.

‡ Epidote includes clinozoisite.

1. Diorite, near Littleton.
2. Diorite, near Lancaster.
3. Quartz diorite, near Littleton.
4. Quartz diorite, near Lancaster.
5. Granodiorite (biotite is the pleochroic green variety) near Littleton.
6. Quartz monzonite, between Piermont and Orford.
7. Granite, between Piermont and Orford.

TABLE 7

APPROXIMATE AVERAGE MODES, OLIVERIAN PLUTONIC SERIES

Minerals	1				2	3	4	5
	a	b	c	d				
Quartz	32	33	31	34	14	6	35	28
Potash feldspar *	1	12	32	45	37	59	35	10
Plagioclase	61	48	29	15	31	29	21	33
Amphibole †	2	1		tr	12	4		3
Biotite	4	4	6	5	5	2	4	14
Muscovite	tr	tr	1	1			2	2
Opaque oxides	tr	1	tr	tr	tr	tr	tr	tr
Opaque sulfides		tr		tr			tr	tr
Apatite	tr	tr	tr	tr	tr	tr	1	tr
Sphene	tr	tr	tr	tr	1	tr	tr	tr
Epidote	tr	1	1	tr	tr	tr	2	10
Chlorite	tr	tr	tr	tr	tr	tr	tr	tr
Average percent of anorthite in plagioclase	25	22	24	20	33	21	11	22

* Potash feldspar is chiefly microcline and orthoclase.
† Amphibole is hornblende.

1. Granite, quartz monzonite, and granodiorite.
   a. Quartz diorite.
   b. Granodiorite.
   c. Quartz monzonite.
   d. Granite.
2. Hornblende-quartz monzonite.
3. Syenite.
4. Lebanon granite.
5. Border gneiss of Lebanon granite, granodiorite phase.

TABLE 8

APPROXIMATE AVERAGE MODES, NEW HAMPSHIRE PLUTONIC SERIES

Minerals	1	2			3	4	5			6	7	8
		a	b	c			a	b	c			
Quartz	3	31	16	27	29	18	32	29	26	27	33	31
Potash feldspar *			6	15	19	33	15	30	45	46	43	28
Plagioclase	36	52	57	48	33	25	36	23	13	16	17	29
Amphibole	27	1	1	tr	1							
Biotite	1	12	17	10	15	20	12	14	10	7	4	5
Muscovite	2			tr		tr	5	4	5	2	3	7
Opaque oxides	tr	1		tr	tr	3		tr	tr	tr	tr	
Opaque sulfides		tr			tr		tr	tr	tr	tr	tr	
Apatite		tr	1	tr	tr	1	tr	tr	tr	tr	tr	
Sphene	2	tr	2	tr								
Epidote	14	3		tr	tr		tr			1		
Chlorite	14			tr	3	tr				1		
Calcite	3				tr							
Garnet		tr		tr	tr		tr	tr	1			
Average percent of anorthite in plagioclase	5	14	40	40	34	23	27	26	20	18	20	

* Potash feldspar is chiefly orthoclase and microcline

1. Diorite. Amphibole is hornblende, muscovite is "sericite," and sphene is "leucoxene."
2. Quartz diorite:
   a. Remick quartz diorite.
   b. Spaulding quartz diorite (Lake Sunapee area).
   c. Winnipesaukee quartz diorite. Percent of potash feldspar may be too high.
3. Bethlehem gneiss.
4. Quartz monzonite of Norway Rapids.
5. Kinsman quartz monzonite:
   a. Phase without large phenocrysts of potash feldspar.
   b. Phase with large phenocrysts of potash feldspar.
   c. Meredith granite phase.
6. French Pond granite.
7. Binary granite. (Billings)
8. Binary granite. (Chayes, 1952)

TABLE 9

APPROXIMATE AVERAGE MODES, PLUTONIC ROCKS OF THE WHITE MOUNTAIN SERIES

Minerals	1						2				3		4	5	6	7	8	9	10	11	12	13	14	15
	a	b	c	d	e	f	a	b	c	d	a	b												
Quartz					1				3	10	2	3	11	12	2		7	13	15	28	25	24	32	29
Potash Feldspar *							tr		4	2	17	33	8	36	73	70	73	69	59	58	63	61	50	59
Plagioclase	75	66	49	52	63	95	45	50	55	63	65	48	57	40	15		11	10	24	2	8	9	11	7
Olivine	16	10					4											tr		1	tr			
Pyroxene	1	18	18	30		2	5	7	16		4	1		1	2	2	1	1		2	tr		tr	
Amphibole			22		24		25	19	1	9	5	5	16	6	7	8	7	7		6	4	3	6	tr
Biotite	1	1		4			12	20	7	15	5	6	6	tr	1	tr	1	tr	2	3	tr	3	1	5
Opaque oxides	7	5	5	9	2				11		1	3		4	tr	tr	tr	tr			tr	tr	tr	tr
Opaque sulfides											tr	tr		tr	tr	tr	tr				tr		tr	tr
Nephelite																14								
Sodalite																6								
Apatite									3		tr	1	tr	1	tr	tr	tr	tr			tr	tr	tr	tr
Accessories and alteration minerals			6	5	10	3	9	4		1	1		2											
Average percent anorthite in plagioclase	55	55	55	50	50	55	45	35	45	46	25	30	42	30	15		25	20	15	10	20	20	10	12

* Chiefly microperthite, but also some orthoclase and anorthoclase.

1. Gabbro:
   a. Olivine gabbro (ossipyte). Mt. Tripyramid.
   b. Olivine-pyroxene gabbro. Olivine is solid solution consisting of 48% forsterite, 52% fayalite. Pyroxene is solid solution consisting of 54% diopside, 27% hedenbergite, 12% $MgSiO_3$, 7% $FeSiO_3$, Biotite has 15.5% FeO, 14.2% MgO. Mt. Tripyramid and east of Crawford Notch.
   c. Pyroxene-hornblende gabbro. Amphibole is basaltic hornblende, brown in thin section. Pyroxene similar to that in olivine-pyroxene gabbro. Mt. Tripyramid and Belknap Mountains.
   d. Pyroxene gabbro. Pyroxene similar to that in olivine-pyroxene gabbro. Mt. Tripyramid and Merrymeeting Lake stock.
   e. Hornblende gabbro. Amphibole is basaltic hornblende, brown in thin section, and also hornblende that is light-green in thin section. Merrymeeting Lake stock.
   f. Anorthosite. Mt. Tripyramid.
2. Diorite:
   a. Hornblende diorite, Pawtuckaway Mountains.
   b. Diorite, Belknap Mountains.
   c. Hypersthene diorite (norite). Pyroxene is 6% hypersthene, 10% augite. Mt. Tripyramid.
   d. Quartz diorite. Amphibole is hornblende. Three and three-quarter miles south-southeast of Franconia.
3. Monzonite:
   a. Monzodiorite. Pyroxene is chiefly clinopyroxene, but there is a little hypersthene. Amphibole is hornblende. Biotite has 20.88% FeO, 2.33% Fe_2O_3, and 10.04% MgO. Belknap Mountains.
   b. Monzonite. Pyroxene is clinopyroxene. Amphibole is hornblende. Biotite contains 12.74% FeO, 1.31% FE_2O_3, and 16.75% MgO. Average of several areas.
4. Granodiorite. Amphibole is hornblende. Merrymeeting Lake stock.
5. Quartz monzonite. Pyroxene is clinopyroxene. Amphibole is hornblende. Average of several areas.
6. Syenite. Pyroxene is solid solution, consisting of 90% hedenbergite, 10% diopside. Amphibole is hastingsite in some specimens, soda hornblende in others. Biotite has high FeO/MgO ratio. Average of many areas.
7. Nephelite-sodalite syenite. Pyroxene is aegirine-augite, amphibole is hastingsite. Red Hill.
8. Quartz syenite. Pyroxene is hedenbergite with small amount of diopside in solid solution. Amphibole is hastingsite in most cases, but on Mt. Tripyramid is a pleochroic brown hornblende. Average of several areas.
9. Porphyritic quartz syenite. Olivine is fayalite, pyroxene is hedenbergite, amphibole is hastingsite. Average of several areas.
10. Rhyolite. Merrymeeting Lake stock.
11. Granite porphyry. Olivine is fayalite, pyroxene is hedenbergite, amphibole is hastingsite. Average of several areas.
12. Mt. Osceola granite. Olivine is fayalite, pyroxene is hedenbergite, amphibole is hastingsite and soda hornblende. Average of several areas.
13. Hastingsite granite, hastingsite-biotite granite phase. Biotite is lepidomelane. Amphibole is hastingsite. Average of several areas.
14. Riebeckite granite. Amphibole is riebeckite; astrophyllite is an accessory in some specimens. Average of several areas.
15. Conway granite. Biotite is lepidomelane. Average of several areas.

TABLE 10
STRATIGRAPHY, EASTERN VERMONT
(After J. B. Thompson, 1952)

Formation	Lithology	Thickness in feet
Meetinghouse slate	Dark-gray slate, some thin beds of quartzite	1000 ?
Gile Mountain formation	Gray to black phyllite, quartzose phyllite, micaceous quartzite	0-5000
Standing Pond volcanics	Green chlorite schist, some buff to white schistose soda-rhyolite	1000
Waits River formation	Dark-gray phyllite, gray calcareous phyllite, dark-brown arenaceous limestone	5000
Northfield slate	Gray to black slate or phyllite	700
Shaw Mountain formation	Quartzite, quartz conglomerate, limestone, g.een chlorite schist, buff soda-rhyolite tuff	0-500
— Unconformity —		
Cram Hill formation	Quartzite, gray to black rusty weathering phyllite, interfering with meta-volcanics	6000
Moretown formation	Gray-green micaceous quartzite, quartz-muscovite-chlorite schist, and green chlorite schist	3700
Stowe formation	Gray-green quartz-sericite-chlorite schist or phyllite, with interbedded green schists	900
Ottauquechee formation	Thick-bedded quartzite and black phyllite, interbedded with gray-green quartz-sericite-chlorite schist	1400
Pinney Hollow formation	Gray-green quartz-sericite-chlorite schist, interbedded in upper part with green schists	3000
Hoosac formation	Gray or black schist with albite porphyro-blasts; quartzite, dolomite, green schists, and microcline-augen gneiss	2700
Tyson formation	Conglomerate, graywacke, schist, micaceous quartzite, and marble	0-600
— Unconformity —		
Pre-Cambrian	Schist, gneiss, amphibolite, marble and calc-silicate rock	

TABLE 11
STRATIGRAPHY, LOWELL-FITCHBURG AREA, MASSACHUSETTS
(After R. H. Jahns, 1952)

Formation	Lithology	Thickness (feet)
"Bolton" gneiss	Coarse-grained muscovite-biotite gneiss with thin limestone beds; many amphibolite members	12,000 +
Brimfield schist	Fine-grained quartz-sericite-andalusite schist	3600-4500
Harvard conglomerate	Conglomerate with pebbles of quartzite and slate	0-600
Merrimack quartzite	Impure quartzite and arenaceous phyllite	6000+

TABLE 12.

COMPARISON OF THE PRINCIPAL PLUTONIC SERIES

	White Mountain	New Hampshire	Southeastern New Hampshire (Hillsboro)	Oliverian	Highlandcroft
1. Stratigraphic age	Younger than unconformity between Devonian and Mississippian (?)	Younger than Lower Devonian older than Mississippian (?)	Younger than Lower Devonian, older than Mississippian (?)	Younger than Middle Silurian, probably younger than Lower Devonian	Pre-Silurian
2. Age relative to regional metamorphism	Younger	Synchronous in part	Synchronous in part	Older, possibly synchronous	Much older
3. Consanguineous volcanics	Present	Absent	Absent	Absent	Absent
4. Foliation	Very rare	Common, much of it primary	Common, much of it primary	Common, much of it primary	Where present, is secondary
5. Lineation	Absent	Present	Present	Present	Absent
6. Texture	Hypidiomorphic granular	Granoblastic to hypidiomorphic granular	Granoblastic to hypidiomorphic granular	Strongly granoblastic	Hypidiomorphic granular, excep lepidoblastic where foliated
7. Pegmatite	Rare	Common; white	Common; white or pink	Common; pink	Rare
8. Structural relations	Discondant; ring-dikes, stocks, and batholith	Concordant; large sheets and lenses. Youngest member (binary granite) is cross-cutting	Concordant; large sheets and lenses. Youngest member (massive binary granite) is cross-cutting	Concordant; mostly as core of large domes	Cross-cutting irregular bodies
9. Origin	Magmatic	Binary granites are magmatic. Other members considered magmatic by some, migmatites by others.	Binary granites are magmatic. Some of other members are migmatites	Considered magmatic by some, metamorphosed volcanics by others, and migmatites by still others.	Magmatic
10. Mineralogy:					
(a) Olivine	Present in gabbro as chrysolite (olivine) and in quartz syenite and granite as fayalite	Absent	Absent	Absent	Absent
(b) Pyroxene	Present throughout series; chiefly diopside-hedenbergite series; some augite in gabbro, a little aegerine-augite in special types	Absent	Absent except in Exeter diorite	Absent	Absent
(c) Amphibole	Present throughout series; common hornblende in mafic end of series: hastingsite, soda hornblende, and riebeckite in siliceous end of series	Common hornblende, chiefly confined to diorite, quartz diorite, and granodiorite	Common hornblende throughout series	Common hornblende; not abundant in most of rocks	Common hornblende
(d) Biotite	Persistent, but relatively less important than other mafic minerals	Principal dark mineral	Principal dark mineral	Principal dark mineral	Common
(e) Muscovite	Absent	Persistent	Persistent	Persistent	Absent, except as secondar mineral
(f) Quartz	Generally confined to rocks with high ratio of potash feldspar to total feldspar	Abundant regardless of ratio of potash feldspar to total feldspar	Abundant regardless of ratio of potash feldspar to total feldspar	Abundant regardless of ratio of potash feldspar to total feldspar	Abundant regardless of ratio o feldspar to total feldspar
(g) Nephelite and sodalite	Present, but rare	Absent	Absent	Absent	Absent

INDEX

The following minerals, because they are so common, have not been indexed: biotite, chlorite, feldspar, muscovite, and quartz.

M: indicates reference to bottom of right-hand column of Explanation on the Geological Map in the pocket.

M

N

O

P

Q

R

Z